DECARBONIZATION OF HELICOPTERS: CHALLENGES FOR THE ENGINE MANUFACTURER OF COMPATIBILITY WITH SAF 100% DROP-IN

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Abstract

The document discusses the challenges in decarbonizing helicopter engines by using 100% Sustainable Aviation Fuel (SAF) as a drop-in alternative to conventional jet fuel. It highlights the need for helicopter engines to adapt to these fuels without requiring modifications to existing systems. The variability in the chemical composition of SAFs, which impacts fuel properties like viscosity, surface tension, and distillation, poses significant challenges for engine operability, including ignition and flame stability. The document emphasizes the importance of understanding how these properties affect combustion performance, pollutant emissions, and engine reliability. It also explores how different SAF compositions influence the production of pollutants such as nitrogen oxides and fine particles. Safran's research through various projects has provided insights into how these fuels perform in real-world conditions, revealing that some physico-chemical properties of 100% drop-in SAF must be controlled in future aviation fuel standards.

1. NOTATION

Symbols

ρ_f	Fuel density
σ_f	Fuel surface tension
T_3	Combustor inlet temperature
T_{fuel}	Inlet fuel temperature
$T_{10\%}$	Fuel recovery temperature for 10% mass evaporation
HC	Heat content of the fuel
FAR_{st}	Fuel air ratio in stoichiometric conditions
Cp_{vap}	Specific heat at constant pressure of the fuel in vapor phase
Cp_{liq}	Specific heat at constant pressure of the fuel in liquid phase
FCP	Fuel characterization parameter
FPR	Fuel Parameter Ratio

Acronyms

SAF	Sustainable Aviation Fuel
DCN	Derivated Cetane Number (measured by ASTM D6890)
Safran HE	Safran Helicopter Engines
NOx	Nitrogen Oxides
CO	Carbon monoxide
UHC	Unburned hydrocarbons
nvPM	Non-volatile particle matter

2. INTRODUCTION

With the challenges of reducing aviation's carbon footprint, the world of aeronautics is preparing the compatibility of the civil aircraft fleet with so-called drop-in SAF (Sustainable Aviation Fuel)., Using a Drop-in fuel means that no modifications should be made to the engines, the aircrafts or the infrastructures.

Today, the international standards approve up to 50% of SAF (in volume) in Jet A1, the final blend can be used safely as a Drop-in fuel. By the end of 2024/beginning of 2025, these standards will evolve to include the possibility of using a 100% Drop-in SAF.

In this context, the helicopter world must be an actor following suit both to respect environmental commitments and also to not suffer from specific constraints in the fuel supply chain on airport platforms.

Until now, the certification of helicopter turbo-machines is carried out with Jet A1 fossil fuel. Due to the potential variability regarding chemical composition of SAF (Figure 1), it is essential to assess the functional impact that the variability of physico-chemical properties can induce.

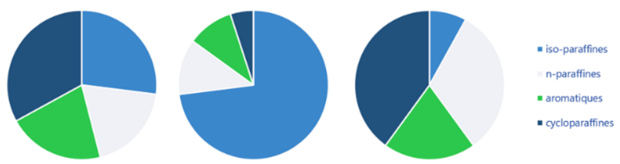

Figure 1: Example of the variability of the composition of fuels depending on their production process: on the left the jet-A1 of fossil origin, in the center the typical composition of a SAF obtained by the HEFA process doped with 10% aromatics and on the right with a CHJ-HEFA-SPK

In this article, we focus mainly on the impact of the fuel composition on the operability of the engine, that is to say its ability to ignite (whatever the temperature or altitude conditions) or re-ignite in flight and not go out during rapid deceleration or ingestion of rain, water or ice. To evaluate the impact of the fuel on these aspects, it is therefore necessary to focus on the operation of the combustion chamber and therefore the physicochemical properties of the SAF on all the multiphysical phenomena which take place in the combustion chamber (fuel spraying, evaporation, mixing, combustion).

3. COMBUSTOR SENSITIVITY TO FUEL PROPERTIES

Thus, physical properties such as viscosity and surface tension act directly on the size of the drops of fuel sprayed into the combustion chamber by the injectors. Associated with the distillation curve, these properties directly influence the evaporation of these drops before combustion. As for the chemical properties of the molecules making up the fuel, they help to define the fundamental speed of the flame, its resistance to stretching and even its auto-ignition time. Table 1 below summarizes the influence of each family of molecules on the different physicochemical properties mentioned above.

Properties example	Iso-paraffins	N-paraffins	Cyclo-paraffins	Aromatics
Distillation	Depends on the carbon number distribution			
Flash point	↑↑	=	↓	↓
Viscosity	↑	↑↑	↓	↓↓
Density	↓	↓	↑	↑↑
Surface tension	?	?	?	?
PCI	↑↑	?	↑	↓↓
Cetane number	↑	?	↓	↓↓
Smoke Point	↑	?	=	↓↓

↑ Increases value compared to Jet A1
↑↑ Strongly increases value compared to Jet A1
= Little change in value compared to Jet A1
↓ Reduces value compared to Jet A1
↓↓ Significantly reduces the value compared to Jet A1

Table 1: evaluation of the impact of fuel composition on physical & chemical properties.

Thus the composition of the fuel directly influences each of the parameters (spraying, evaporation, combustion) determining the combustion performance of the combustion chamber which can be summarized as follows:

- Viscosity & surface tension → characteristics of the fuel spray → ignition & extinction performance
- Distillation curve → evaporation of light and heavy fractions → ignition & extinction performance
- Flammability limit, auto-ignition time, fundamental flame speed, resistance to stretching → ignition & extinction performance
- fuel heat content (HC) & density → fuel dosing in open loop regulation (during ignition, deceleration and acceleration).

To this, we can also add the influence of the chemical composition of the fuel on polluting emissions, in particular NOx and fine particles (nvPM) via the modification of the chemical kinetics of combustion.

The combustion chambers of helicopter turboshaft engines and their injection systems can be of various technologies (injection wheel, pre-vaporization tubes, swirlers, gyratory combustion, etc.), the sensitivity to the different properties of the fuel could be different depending on the technologies used. We can for example emphasize that the extinction limit of a chamber equipped with pre-vaporization tubes will be little sensitive to viscosity and surface tension but rather influenced by the distillation curve and the fundamental combustion properties.

3.1. Fuel parameter for operability

The operability of a combustion chamber (extinction & ignition) is mainly driven by the air-fuel mixture in the primary zone located just downstream of the injection systems. Thus at Safran HE, we have chosen to distinguish 2 main effects related to the physico-chemical properties of the fuel :

- atomization and evaporation of the fuel
- then combustion of the air-fuel mixture in the primary zone

For the first point, to assess the influence of the physical properties of the fuel (density, viscosity, surface tension, distillation curve, etc.), Safran HE has chosen to use the "Fuel characterization parameter" as defined in reference 4. Its definition is given below

$$FCP = \frac{\rho_f \,.\, (SMD)^{1.5}}{\log(1+B)}$$

Where :

- SMD is the Sauter mean diameter generated by the injection system inside the combustor
- B is the mass transfer number given by :

$$B = \frac{Cp_{vap}(T_3 - T_{10\%}) + HC \,.\, FAR_{st}}{Cp_{liq}(T_{10\%} - T_{fuel}) + L_{vap}}$$

Of course, the SMD depends on the injection technology used in the combustion chamber. But for a given technology, it only depends on the properties of the fuel. Thus, based on correlations specific to each injection technology (see ref. 5 & 6) which allow to quantify the evolution of the SMD according to the properties of the fluid, it is possible to compare fuels with each other via the Fuel Parameter Ratio (FPR):

$$FPR = \frac{FCP}{(FCP)_{ref}}$$

If the FPR is greater than 1, it means that the fuel will have more difficulty evaporating. Therefore, ignition will be more difficult and the lean flameout limit may be higher.

As an example in Figure 2 below, we studied the sensitivity of the FPR, for a given chamber technology, to a 5% variation in the parameters characterizing the fuel.

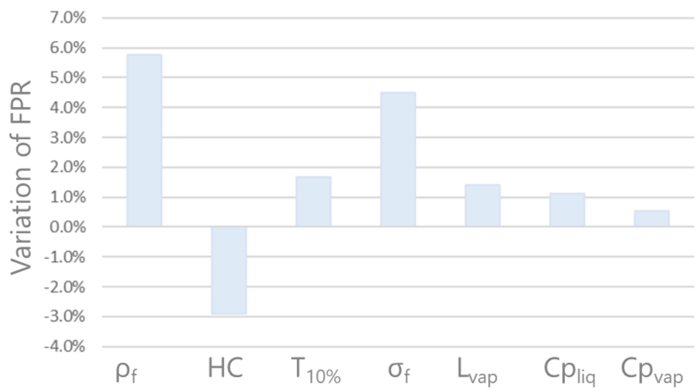

Figure 2: Sensitivity of FPR to fuel properties

For the second point concerning the combustion of the air-fuel mixture in the primary zone, the main parameters to be considered are the fundamental properties of the flame : burning time, self-ignition, fundamental flame speed, resistance to stretching. Unfortunately, these different parameters are not easy to measure and there is no standardized protocol to do so. Therefore, manufacturers including Safran suggest examining the cetane index which can be compared to a self-ignition delay and whose measurement is perfectly controlled and standardized, because defined in the standards for these road fuels diesel type. There are 2 protocols defined by ASTM to measure the Derivated Cetane Number (DCN) :

- D6890 : Ignition Quality Tester
- D7668 : Cetane Ignition Delay.

Both methods give equivalent results and allow fuels to be classified according to their ability to self-ignite. Thus, the higher the cetane index, the shorter the self-ignition time. For operability, it is therefore preferable to have a high cetane index.

3.2. Evaluation of the impact on pollutant emissions

Concerning pollutant emissions, since fuels all have a similar HC, the flame temperatures will be quite close and therefore the impact on the production of carbon monoxide and unburned hydrocarbons will be moderate. The same is true for nitrogen oxides.

Concerning fine particles, certain families of molecules such as aromatics promote the production of soot during the combustion of the fuel. Consequently, a fuel rich in aromatics is likely to produce more fine particles than a fuel with a low content.

4. SUSTAINABLE AVIATION FUELS : VARIABILITY OF PHYSICOCHEMICAL PROPERTIES

Some of the physicochemical properties of the fuels cited above do not appear in the standards defining aeronautical fuels (ref. 7: ASTM D1655 & ref. 8: ASTM D7566), in particular the surface tension and the DCN.

The first step therefore consists of quantifying the variability of the different properties mentioned above of fossil aeronautical kerosenes. For this we can rely on the data appearing in the World Fuel Sampling Program (ref. 1), the PQIS (ref. 2) and in the document "Jet Fuel Properties by James T. Edwards" (ref. 3).

4.1. Conventional jet fuels properties

World Fuel Survey collects data on aviation fuels properties depending of world regions or fuel type.
Figure 3 shows a relatively little dispersion for density when compared occidental jet fuels to Africa fuels. The average density is around 0.81g/cm3 for USA fuels against 0.78g/cm3 for Africa fuels. The density range is similar for any type fuels analyzed (between 0.80 and 0.82g/cm3). The same tendency (a lower dispersion) is observed for heat content (Fig. 3). Average surface tension is from 23.5mN/m for Africa fuels to 25mN/m USA fuels. Surface tension can reach 25.5 depending of the fuel (JP-5) (Fig. 3). The observed variability can be linked to the method.

As a conclusion, both density and surface tension are relatively low dispersed (+/-2.5%). For heat content, the dispersion is less than 2%. %. For these properties, the low dispersion observed may be due to a well-controlled fuel composition based on years and years of refinery process experience.

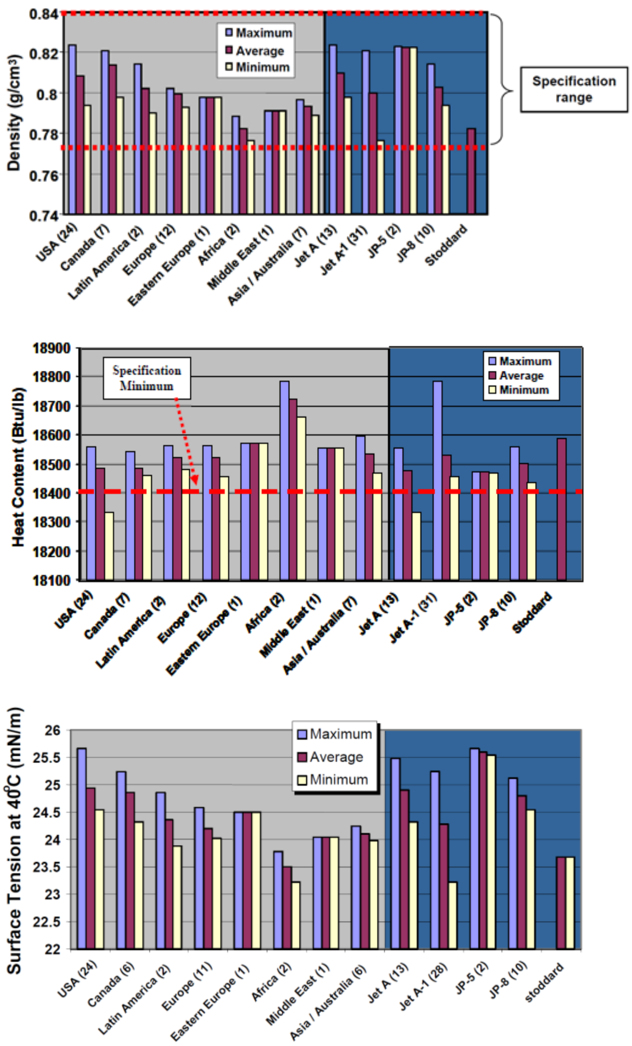

Figure 3: World Fuel Survey (Ref.1) : density, heat content and surface tension variability of jet fuels

With all data collected in the ref. 1, it is possible to calculate the FPR (for a given combustor technonology) of the different fuels and to deduce the range of variation covered by the feedback. Figure 4 shows that aviation fuels remain in a FPR range of between 0.9 and 1.15 with disparities depending on the continents: in North America, the average FPR is around 1.07 while it is 0.98 in the rest of the world.

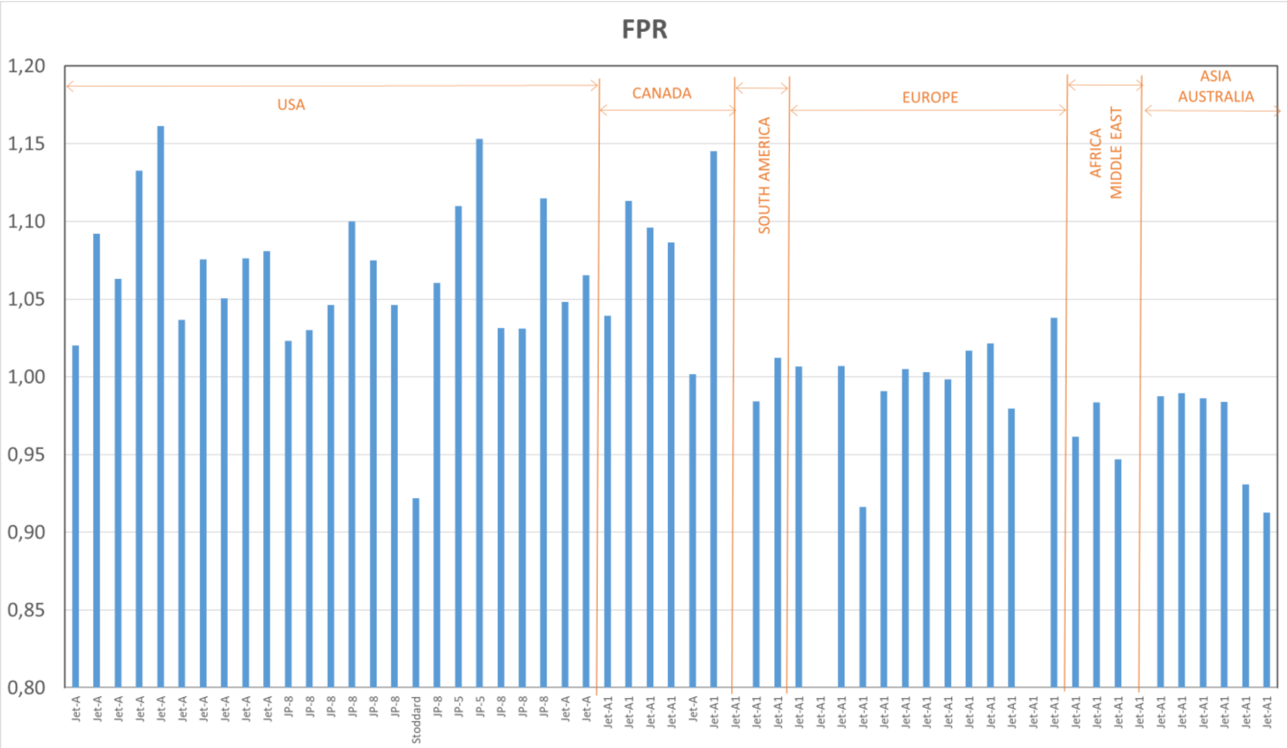

Figure 4: Aggregated FPR for conventional jet fuels (JP-8, Jet A, Jet A-1, JP-5) for a given Safran HE combustor technology (datas from ref. 1)

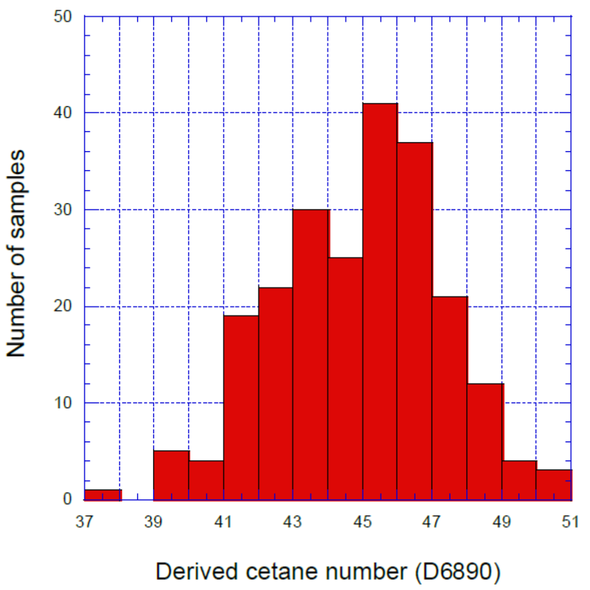

Figure 5: Aggregated DCN data for conventional jet fuels (JP-8, Jet A, Jet A-1, JP-5) (see ref. 3)

Reagrding the DCN, some datas are available in ref. 3 and shown in the figure 5 above. It appears that for aviation fuels the DCN is in the range of 39 to 51 with an average around 45. The observed variability can be linked to the composition of the fuel especially the aromatic and cycloparafin contents (Table 1).

To summarize, the feedback from conventional aviation fuels covers a range of FPR from 0.9 to 1.15 and DCN between 39 & 51.

4.2. Sustainable aviation fuels (SAF)

With the introduction of SAFs in increasingly large quantities, it is relevant to examine the influence of the composition of these fuels on the parameters cited above.

Figure 6 below shows for some fuel samples the possible variability of properties depending on the type of SAF. Density can vary from 750 to 820kg/m^3. The same variability is observed for viscosity (from 3 to 6cst at -20°C) and distillation (from 170 to 190°C for

10% recovered). The variability is lower for specific heat of combustion (PCI) (from 43 to 44MJ/kg).

DCN varies from 18 (ATJ-SPK) to 60 (FT-SPK) depending of the type of SAF (Fig. 6). A large DCN range for the same type of SAF is also observed. For example, an ATJ-SPK SAF can have a DCN between 18 and 48.

As shown in Fig. 1, the chemical composition of SAF can differ from a fossil fuel in:

- Cycloparaffin and aromatic contents
- A change of n-/iso-paraffin ratio

And, as shown in Table 1, the chemical composition has a direct impact on fuel properties.

The higher variability observed for SAF properties compared to fossil fuels is due to the possibility of using a large type of feedstocks (alcohols, oils, algae, syngas, etc.) and each type of SAF has its own production process. This increases the variability in chemical composition and therefore of the physico-chemical properties.

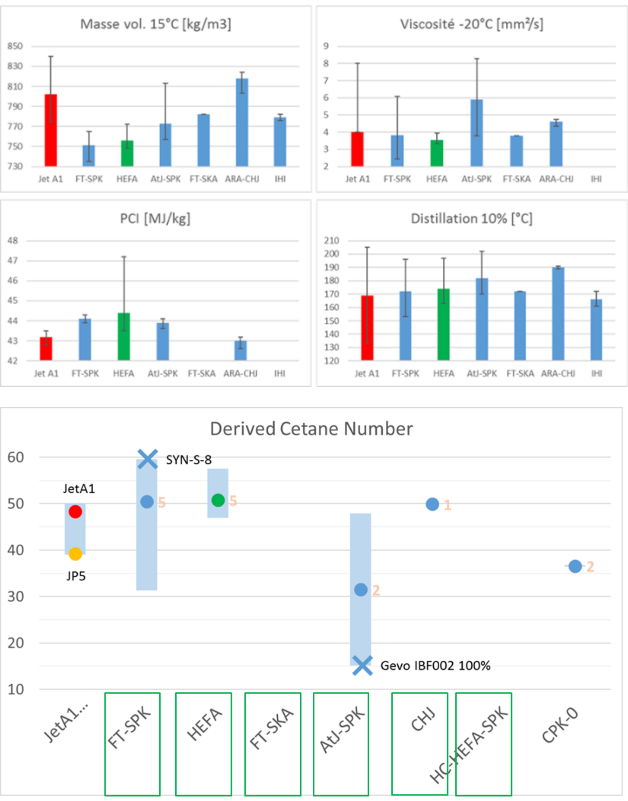

Figure 6: Example of physicochemical properties of of some SAF samples.

In summary, by drawing a DCN vs FPR diagram (figure 7), we can see that some of these fuels are not covered by the feedback from fleets in service.

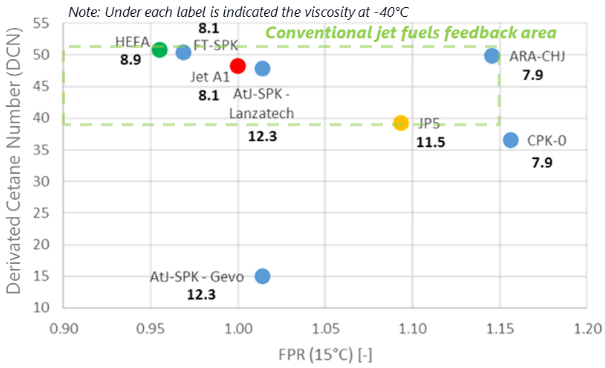

Figure 7: DCN vs FPR for different aviation's fuels compared to the feedback area of conventional fuels.

5. SAFRAN FEEDBACK ON SAF

Through various research programs, Safran HE has been able to quantify the impact of some SAF (non-drop-in) on the combustion performance of a combustion chamber.

5.1. Operability

As part of the European JETSCREEN project, the experiments carried out by the DLR on a swirl injection system demonstrated that there was a close correlation between the DCN and the lean extinction limit. These results have been confirmed in the reference 9 by Zheng et al. and reported here in the figure 8.

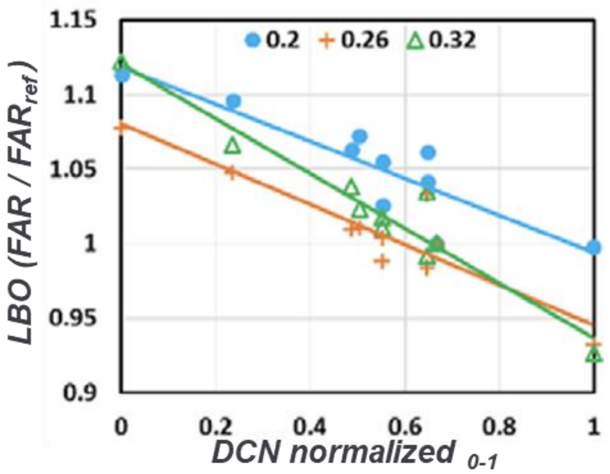

Figure 8: Linear relationship between DCN and LBO performance for 3 air flow conditions (cf. ref. 9).

As part of the French VOLCAN project, the extinction limit of a Safran HE engine was characterized as a function of the starting speed of a deceleration maneuver. The hierarchy found between the two fuels SAF HEFA & ATJ and the Jet-A1 taken as a reference is consistent with the cetane index values of these fuels. Thus the HEFA having a DCN close to 60 slightly lowers the lean extinction limit of the engine compared to the Jet A1 whose DCN was measured around 45. Concerning the ATJ whose DCN is less than 20, it significantly degrades the lean extinction limit of the combustion chamber (see figure 9 below). In this case, it would be advisable to review the deceleration stops in order to protect the engine from any risk of flame out during a rapid deceleration maneuver.

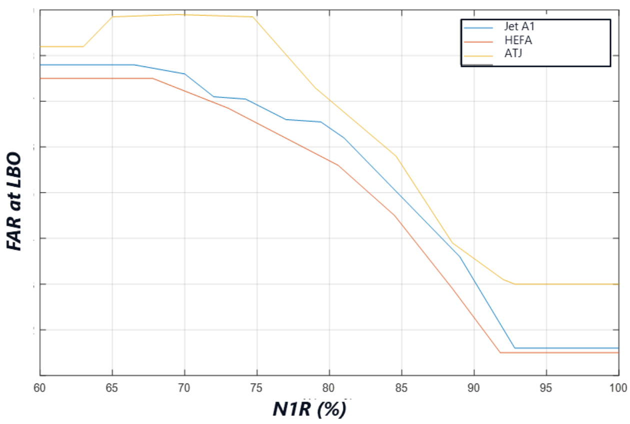

Figure 9: Lean extinction limit measured on a Safran HE turboshaft engine for different SAFs depending on engine speed

Concerning the impact of fuel on the ignition capabilities of the turbomachine, initial tests were carried out in the PPrime (CNRS) laboratory as part of the VOLCAN project in order to characterize the probability of ignition of a mist of drops with an aeronautical spark plug. The results are summarized in figure 10 below which shows that in depressed conditions (case of re-ignition at altitude) the ATJ is more difficult to ignite than the Jet-A1 while the HEFA facilitates ignition.

Once again, the Cetane index appears to be a relevant parameter for evaluating the impact of fuel on the ignition capabilities of a gas turbine. The next step would therefore be to confirm these results with engine tests or partial combustion chamber tests under representative conditions (altitude, temperature).

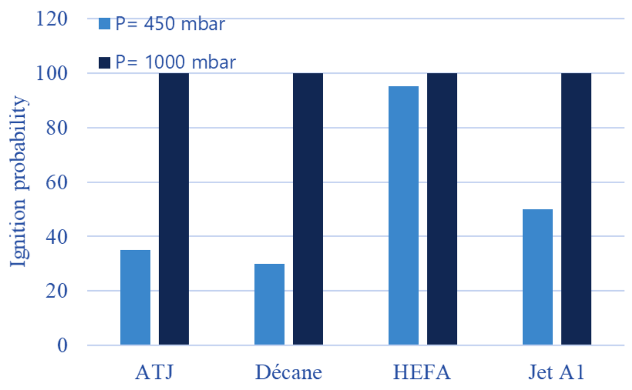

Figure 10: ignition probability of a mist of droplets for 2 ambient pressures

5.2. Pollutant emissions

During the VOLCAN project and other SAF use demonstration programs, Safran HE has carried out measurements of pollutant emissions (NOx, CO, UHC, nvPM) at the exhaust. An example of results is shown in the figure 11 below with a HEFA fuel.

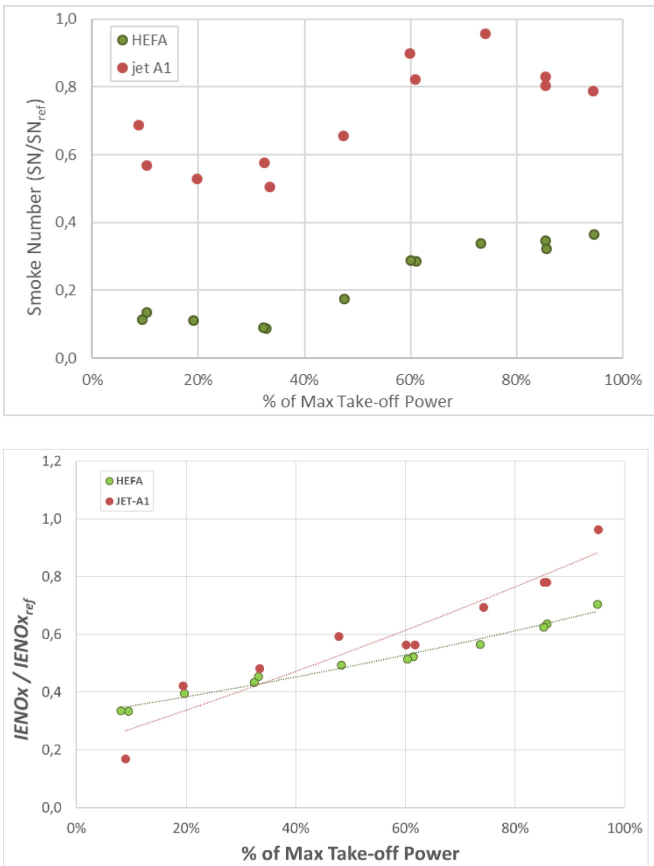

Figure 11: Pollutant emissions on a Safran HE turboshaft engine for HEFA without aromatics compared tout Jet-A1.

HEFA is composed of paraffins with no aromatics. Smoke number and NOx were measured at different % of Max Take-off Power. HEFA slightly modifies NOx emissions especially at higher take-off power (> 60%). HEFA leads to an important decrease of smoke number at any % of max Take-off Power compared to Jet A1. This indicates lower emissions of fine particles (nvPM). The result is directly linked to the absence of aromatics in HEFA compared to the Jet A1 which contains around 16% aromatics.

All the tests carried out at Safran HE show that SAF fuel (HEFA with different aromatics content between 0 and 16%) only very slightly modifies gaseous emissions (NOx, CO, UHC). On the other hand, the aromatics content of the fuel directly influences the production of fine particles. With a SAF without aromatics, the quantity of nvPM is divided by approximately 2.

6. CONCLUSIONS

In this paper, the direct correlation between chemical composition of aeronautical fuels and their physicochemical properties has been highlighted.

Certain of these properties can have a significant impact on the performance of the combustion chamber of a gas turbine.

The first and most important point is to ensure that sustainable aviation fuels will not impact operability, in order to preserve the engine's in-flight relighting capabilities and avoid any risk of flameout, particularly during rapid deceleration maneuvers. Thus, to guarantee the airworthiness of helicopter gas turbines, Safran HE proposes to control certain physicochemical parameters of the fuel such as:

- the derived cetane index reflecting the impact of the chemical composition on the fundamental parameters of combustion
- a set of properties via the FPR parameter making it possible to measure the impact of the fuel on its capacity to evaporate when it is injected into the combustion chamber.

For the latter, the simplest is to add surface tension control to the physical properties of a SAF defined in ASTM D1655 & D7566 standards.

Regarding the impact on pollutant emissions of the use of SAF, the results show that gaseous emissions (NOx in particular) will be almost unaffected and that the reduction in the aromatic content of SAF compared to Jet-A1 should lead to a significant reduction in fine particle emissions.

The next update of the ASTM standards defining a 100% drop-in SAF will have to take into account all of these aspects thanks to the joint studies carried out by aeronautical turbine manufacturers which will define the physicochemical properties of a SAF and their limits.

Beyond the scope of the performance of a gas turbine combustion chamber, there are also other important aspects to address: material compatibility, impact on fuel measurement and dosing systems, etc…

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