PureJet

Pyrolysis oil **U**pgrading for the production of **Re**newable **Jet**fuel

TIND221002
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Publiek Eindrapport

CONTENT

Annexes (Confidential)

Abbreviations

ASTM	American Society for Testing and Materials
FBP	Final Boiling Point
FPBO	Fast Pyrolysis Bio-Oil
GHG	GreenHouse Gas
HPO	Hydrotreated Pyrolysis Oil
IBP	Initial Boiling Point
SAF	Sustainable Aviation Fuel
WP	Work Package

Deel 1: Gegevens Project (BTG)

Projectnummer:	TIND221002
Projecttitel:	Purejet: Pyrolysis oil Upgrading for the production of Renewable Jetfuel
Penvoerder:	BTG Biomass Technology Group BV
Medeaanvragers:	Technische Universiteit Delft SkyNRG BV
Projectperiode:	01-03-2022 t/m 28-02-2025
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Het project is uitgevoerd met subsidie van het Ministerie van Economische Zaken, Nationale regelingen EZ-subsidies, Topsector Energie uitgevoerd door Rijksdienst voor Ondernemend Nederland.

Deel 2: Inhoudelijk Eindrapport (Publiek)

Samenvatting

Duurzame luchtvaartbrandstoffen (SAF) kunnen een rol spelen in de decarbonisatie van de luchtvaartsector. De productie van dergelijke brandstof uit biomassa van de tweede generatie is een uitdaging en nog niet commercieel haalbaar.

Het PureJet-project (**P**yrolysis oil **U**pgrading for the production of **RE**newable **JET**fuel) is gestart om een kerosine waardeketen te ontwikkelen via snelle pyrolyse van duurzame biomassa. Pyrolyse olie (FPBO) kan worden geproduceerd uit diverse biomassa's en residuen. De technologie is in volle ontwikkeling en wordt tegenwoordig commercieel toegepast. FPBO moet echter grondig worden opgewaardeerd om het in de transportsector te kunnen gebruiken. Katalytische behandeling van FPBO met waterstof is een veelbelovende aanpak om hoogwaardige brandstoffen te verkrijgen. In het PureJet-project ligt de focus op de productie van een drop-in vliegtuigbrandstof. Het PureJet consortium werd gevormd door BTG Biomass Technology Group BV, de Technische Universiteit Delft, en SkyNRG bv.

Het uitgangspunt van de ontwikkeling is FPBO uit een commerciële pyrolyse-installatie die zaagsel als biomassavoeding gebruikt. Vervolgens is de FPBO onder verschillende procesomstandigheden gehydrogeneerd bij BTG. Het resulterende product is gedestilleerd en de kerosine-fractie is in detail geanalyseerd. Vergeleken met een conventionele Jet A1 is de dichtheid van PureJet relatief hoog, wat echter ook resulteert in een hogere volumetrische energiedichtheid, maar uiteindelijk voldeed de brandstof aan alle specificaties. Het belangrijkste verschil tussen PureJet en JetA1 betreft de chemische samenstelling. PureJet is zeer rijk aan cycloalkanen (75-85%), terwijl JetA1 meer paraffinische componenten bevat. De menging van JetA1 en PureJet (0-100%) is onderzocht en alle monsters bleken homogeen en stabiel te zijn over een periode van maanden. Voor de PureJet-waardeketen is een GHG-emissiereductie van meer dan 70% haalbaar, mits de waterstof intern of uit hernieuwbare bronnen wordt geproduceerd.

De verbrandingseigenschappen van PUREJET-brandstoffen (mengsels) werden op fundamenteel niveau getest in een voorgemengde en voorverdampte bunsenbranderopstelling en uiteindelijk ook in een microgasturbinemotor. In de turbinetesten werden vergelijkbare NOx- en CO-emissies gemeten voor SAF-mengsels en JetA1, met afwijkingen van minder dan 15 ppm NOx ten opzichte van JetA1.

SkyNRG voerde een brandstof- en marktanalyse uit en dit liet zien dat PureJet-kerosine een hoogwaardige vliegtuigbrandstof is, geschikt voor de commerciële luchtvaart. De technologie zal zich verder moeten ontwikkelen tot een gecontroleerd en stabiel productieproces. De studie toonde aan dat PureJet-kerosine de potentie heeft om een commerciële SAF-productieroute te worden, met mogelijkheden om vanaf 2035 de Europese SAF-markt te betreden en te penetreren.

Summary

Sustainable Aviation Fuels (SAF) can play an important role in the decarbonization of the aviation sector. The production of such fuel from 2nd generation lignocellulosic biomass is challenging and not yet commercial.

The PureJet project (**P**yrolysis oil **U**pgrading for the production of **RE**newable **JET**fuel) has been initiated to develop a SAF value chain via fast pyrolysis of sustainable biomass. Fast Pyrolysis Bio-Oil (FPBO) can be produced from a variety of biomasses and residues, and the technology is maturing and nowadays implemented commercially. However, FPBO needs severe upgrading to enable its use in the transportation sector, and hydrotreatment of FPBO is a promising approach to obtain high quality fuels. In the Purejet project the focus is on the production of a drop-in jetfuel, and the consortium consisted of BTG Biomass Technology Group BV, Delft University of Technology and SkyNRG BV.

The starting point of the development is FPBO from a commercial fast pyrolysis plant using sawdust as biomass feed. Subsequently, the FPBO has been hydrotreated at BTG under varying process conditions. The resulting product is distilled, and the jet-fraction has been analyzed in detail. Compared to a conventional Jet A1 the density of PureJet is relatively high which also results in a higher volumetric energy density, but basically all specifications could be met. The major difference between PureJet and JetA1 concerns its chemical composition. Purejet is very rich in cycloalkanes (75-85%) whereas JetA1 contains more paraffinic components. The blending of JetA1 and PureJet (0-100%) has been investigated, and all samples appeared to be homogeneous and stable over a period of months. For the PureJet value chain GHG emission reduction values of over 70% are achievable provided the hydrogen is produced internally or from renewable resources.

The PUREJET fuels combustion characteristics were tested on a fundamental level in a premixed-prevaporised Bunsen burner setup and eventually on a micro gas turbine engine. In the latter tests, similar magnitudes of NOx and CO emissions were measured for SAF blends and JetA1, with deviations of <15ppm of NOx from the values of JetA1.

SkyNRG performed a fuel & market assessment, and it confirmed that PureJet is a high-quality jet fuel suitable for commercial aviation and identified the need for the technology to mature into a controlled and stable production process. It demonstrated the potential for PureJet SAF to become a commercial SAF production pathway with possibilities to roll out and penetrate the European SAF market from 2035 onwards.

Introduction & overall Objectives

Background & challenge

Europe has set ambitious targets to reduce GHG emissions in all sectors of the economy including transport. Aviation is one of the most difficult sectors to decarbonize. Sustainable Aviation Fuels (SAF) currently play a minor role in this industry, but they will be the most important part of the solution. EU targets are a 2% use of SAF in 2025, 5% in 2030, increasing to 63% in 2050. SAF can reduce emissions from the existing aircraft fleet given its compatibility with existing engines and fuel infrastructure. Nowadays, commercial production of SAF is predominantly based on the hydrotreatment of vegetable oils and used cooking oils (UCO). The production of SAF from 2nd generation lignocellulosic resources complying with the sustainability criteria of RED3 (Annex 9A) are under development, but current commercial activities are scarce.

There are several barriers that are limiting the uptake of SAF and can be broadly divided in three categories, namely technical, environmental and commercial. For a SAF to be viable it must meet challenging technical performance and quality criteria i.e. be technically suitable, be truly sustainable in both production of raw materials and processing, and eventually be available in sufficient quantities at a commercially competitive price. A significant hurdle for any new SAF is its certification. It must be demonstrated that a new pathway can produce a fuel that has similar chemical-physical properties and that it behaves sufficiently similarly to conventional jet fuel to gain approval. The approval process is expensive, time consuming and it requires significant amounts of fuel. The challenge is to develop SAF production processes meeting all criteria mentioned above.

Jet fuels consist of n-alkanes, iso-alkanes, cyclo-alkanes and aromatics. Known jet fuel production pathways typically produce certain components of the jet fuel, but not a 100% substitute. For example, HVO is rich in the alkanes and iso-alkanes but no, or hardly any, aromatics. Furthermore, typically a mix of different transportation fuels are produced (kerosene, gasoline and/or diesel). From a combustion point of view the aromatics are not desired, but its presence in jetfuel might be required in view of its seal swelling capacity. Cycloalkanes have the same functional benefits as the aromatics, they have a higher specific energy and likely their combustion results in lower particle emissions. Jet fuels like JP9 and JP10 are specialty fuels for very demanding applications, and for example JP-9 contains methyl-cyclohexane to achieve the required specifications. Therefore, cyclo-alkanes produced from renewable resources might be an interesting additive/drop-in to jet-fuel to improve its sustainability and performance.

PureJet Concept

The PureJet project (**P**yrolysis oil **U**pgrading for the production of **RE**newable **JET**fuel) has been initiated to develop a SAF value chain via fast pyrolysis. Hydrotreatment of fast pyrolysis bio-oil (FPBO) is a promising approach to obtain sustainable cyclo-alkanes from renewable resources. FPBO can be produced from a variety of biomasses and residues, and the technology is maturing and nowadays implemented commercially. However, the FPBO as such is not suitable for direct use as transportation fuel; for example, it is acidic, contains significant amounts of water, and has a relative low heating value compared to fossil fuels. Obviously, severe upgrading will be needed, and typically, a two-step hydrotreatment process is applied to change the functionalities and remove the oxygen. The hydrotreatment process is carried out at elevated pressure and temperature in the presence of a catalyst.

Project Objective

The main objective of the PureJet project was to develop a process to produce a drop-in SAF rich in cycloalkanes which complies with the existing fuel specifications. The product quality will be validated through a pre-tier product validation procedure based on detailed analyses of the chemical composition as well as dedicated combustion tests in a turbine. The outline of the project is illustrated in Fig. 1. Project partners are BTG (upgrading, distillation, jetfuel analysis and sustainability), TU Delft (combustion research and turbine test on labscale), and SkyNRG (assessment jetfuel market & the potential of the PureJet fuel). The specific results of each of the activities will be presented in the next sections.

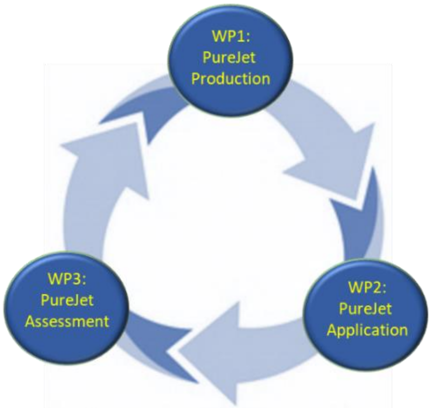


Fig. 1: Outline Purejet project.

PureJet fuel production, separation, purification & analyses

The objective of this activity is to produce a jetfuel from sustainable biomass via the fast pyrolysis route. In the first step the biomass is converted into a liquid called fast pyrolysis bio-oil (FPBO), and subsequently the FPBO is hydrotreated into hydrotreated pyrolysis oil (HPO). From the latter product the jet fraction is obtained by distillation. The overall value chain is schematically shown in Fig. 2.

Fig. 2: Value chain from biomass to jetfuel via fast pyrolysis

The starting point of the Purejet project is FPBO from a commercial fast pyrolysis plant using sawdust as the feedstock. This FPBO is upgraded by a hydrotreatment process, and BTG has several hydrotreaters available on bench- and pilot scale ranging from in capacity from around 1 kg/d feedstock up to 40-50 kg/d feed. These units can be operated 24/7. First the FPBO is stabilized at high pressure (200 bar), elevated temperature (100-300 °C) in a hydrogen atmosphere and in the presence of the proprietary catalyst (Picula™). Then it is further hydrotreated in the presence of a commercial hydrotreating catalyst to remove all the oxygen and saturate aromatic compounds. The product HPO is distilled in three fraction being HPO-naphtha, HPO-Jet and HPO-marine (see Fig. 3). Distillation range for the jetfraction is from 140-150 °C up to 270-280 °C, and typical yield is 45 - 55wt% (HPO basis). Initially, the jetsamples are analysed internally at BTG and the most promising samples have been analysed in detail by a certified external laboratory. Moreover, samples are sent to TU Delft for combustion research and turbine tests.

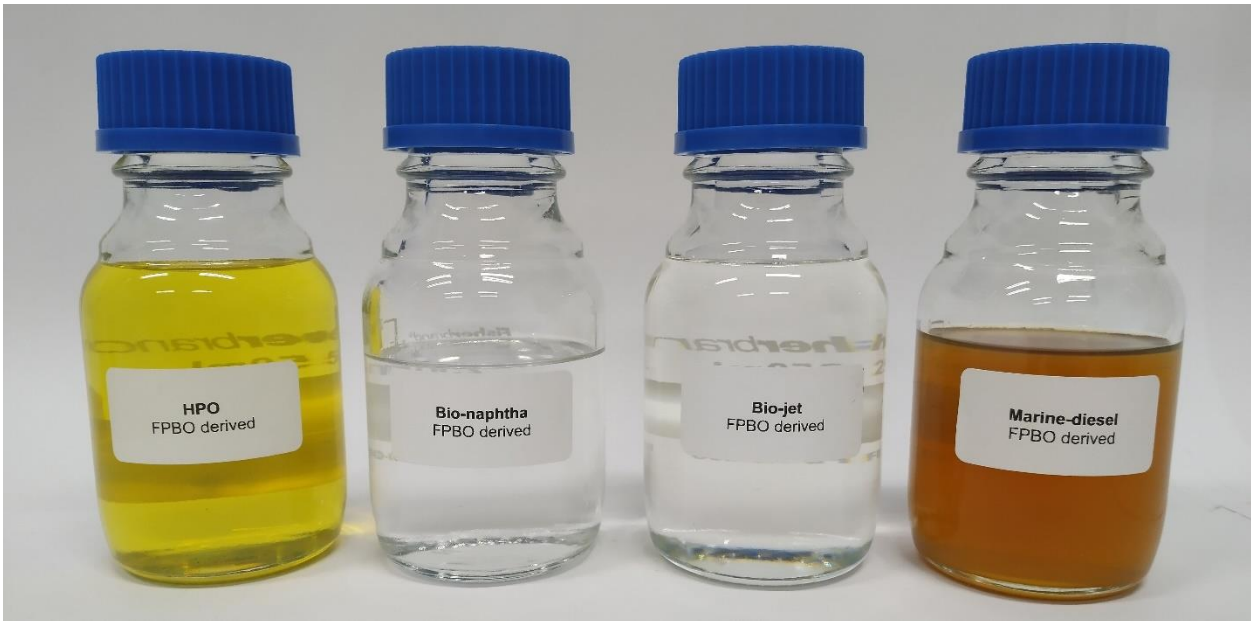


Fig. 3: HPO and distillation fractions

Evaluation of the detailed chemical analysis and the results from the combustion trials have been used to tune process conditions and optimize the jetfuel quality. Table 1 summarizes the chemical-physical properties of the final PureJet sample and its properties are compared to ASTM standards, and positively, in all cases the specifications could be met. Not shown in the table but also the trace metal content has been measured and in all cases the values were below the detection limit. Besides the chemical-physical properties the composition of the PureJet fuel has been analysed using GCxGC FID. The results are presnted in Fig. 4 and Fig. 5. Also, the composition of the Jet A1 sample -provided by TUD and used in combustion trials- is included here for comparison. Additionally, for the PureJet sample a polar analysis according UDR FC-M-102 was performed, but no oxygenates could be detected (all below detection limit).

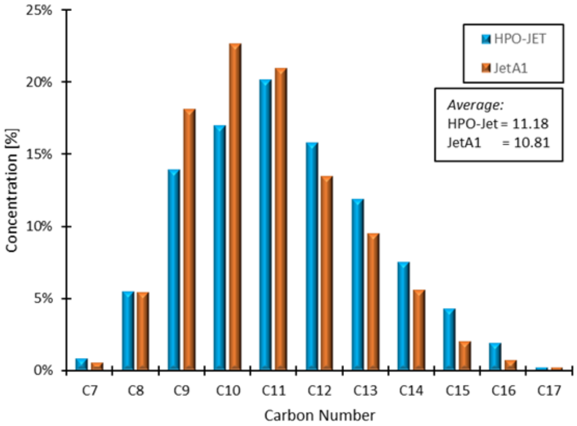


Fig. 4: Carbon Number distribution for PureJet and JetA1

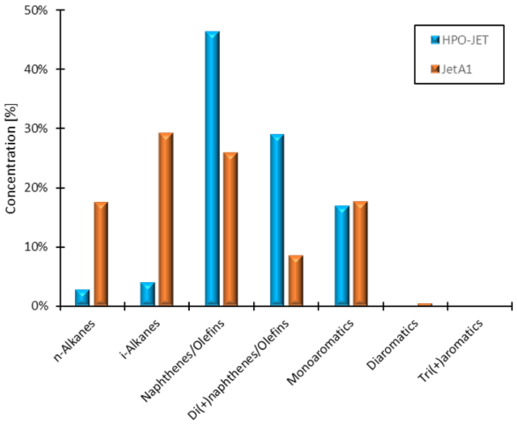


Fig. 5: Composition of PureJet and JetA1

Table 1: Properties of PureJet compared to specifications in the standard

Parameter	Unit	ASTM Specifications			PUREJET
		D1655	D7566	D4054	BTG-4833
Density (T = 15 °C)	kg/L	0.775 – 0.840		0.730–0.800	0.8341
Water	mg/kg			< 75	42
Viscosity (-20 °C)	cSt	< 8			5.074
Viscosity (-40 °C)	cSt		< 12		10.57
Acidity	mg KOH/g	< 0.10		< 0.015	0.006
Flashpoint	°C	> 38		38 - 66	49.7
Freeze Point	°C	< -40 / -47		< -40	-89.1
Net Heat of combustion	MJ/kg	> 42.8		-	43.18
Mercaptane sulfur	mg/kg	< 30			<10
Sulfur content (D2622)	mg/kg	< 3,000		< 15	2.4
Nitrogen (D4629)	mg/kg			< 2	<0.5
Chlorine	mg/kg	< 1			< 1
Smoke Point	mm	>25 or > 18 if napthalenes < 3%			22.4
Napthalene	v%				0.06
Total Aromatics	wt%	< 26.5		8-25 v%	12.7
Mono-Aromatics (MAH)	wt%				12.7
Di-Aromatics (DAH)	wt%				< 0.1
Gum content	mg/100ml	<7			< 1
JFTOT at T ,	°C	260	325		
- Tube rating - Pressure diff	-	<3 < 25 mm Hg			< 1 < 0.1
Cetane number		>35			38.3
IBP	°C				161.0
FPB	°C	<300			264.6

Compared to a conventional Jet A1 the density of PureJet is relatively high which also results in a higher volumetric energy density. The Cetane number is above the minimum value but in the lower range and can be increased by lowering the aromatic content in the fuel by more severe hydrotreatment. However, the major difference between PureJet and JetA1 concerns its chemical composition. Purejet is very rich in cycloalkanes (75-85%) whereas JetA1 contains more paraffinic components. Within the project also the stability and homogenity of JetA1 and PureJet blends have been investigated over the whole range (0-100%) by using a so-called Turbiscan, which enables a quantitative assessment. Over a period of almost 2 months all blends as well as the pure fuels remained homogeneous and appeared to be very stable.

Combustion Research & application of PureJet (blends) in a turbine

Fundamental Combustion Experiments

This part of the project was developed with the objective of obtaining fundamental combustion characteristics of the PUREJET fuels. A premixed-prevaporised Bunsen burner setup was developed to measure laminar burning velocity and emissions associated with fuel-air mixtures of the SAF fuels. These values were compared to those obtained for JetA1-air flames.

Fig. 7 shows the schematic of the setup. The fuel is supplied through a pressure-fed system where the fuel is stored in a diaphragm pressure vessel and is pressurized with nitrogen. The liquid fuel flow is controlled using a Bronkhorst Coriolis massflow controller. The air is supplied through a separate supply line, and is controlled using a Bronkhorst El-Flow massflow controller. The air passes through a heater before being injected in the mixing chamber. The fuel and air mix in the mixing chamber which along with the rest of the Bunsen burner structure is heated using trace heating wrapped around the pipes. This provides heat for vaporization of the liquid fuel and a well-mixed gaseous mixture of fuel and air are obtained at the tip of the Bunsen burner.

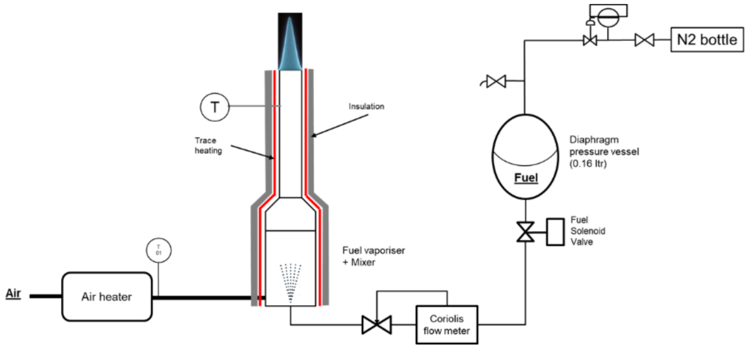


Fig. 6: Schematic of Premixed Prevapourised Bunsen Burner setup

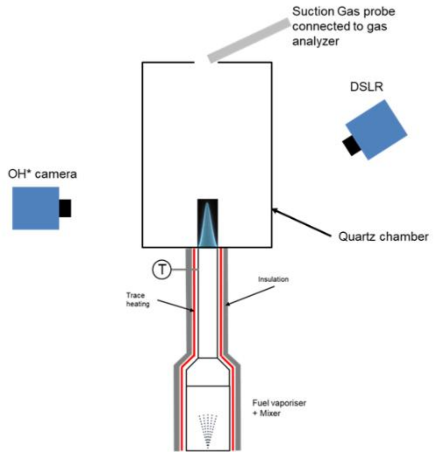


Fig. 7: Enclosed bunsen burner with diagnostics

Measurements were done by imaging the flame and measuring the gas composition at the exit of the chamber enclosing the flame, as shown in Fig. 8. OH* chemiluminescence imaging was done using a FL20BW UV sensitive camera with a bandpass filter (325 +/- 25 nm) and a Nikon D7500 DSLR camera was used to obtain color images of the flame. The OH* images were used to extract a flame front using image processing algorithms as shown in Fig. 9 and Fig. 10. This gives the flame surface area of a steady laminar Bunsen flame. As the inlet massflows of fuel and air are known along with the temperature of the mixture(which is measured upstream of the nozzle exit), using conservation of mass, the velocity of the unburned mixture just before the flame-front can be calculated. This is also the most commonly used definition of laminar burning velocity used in literature.

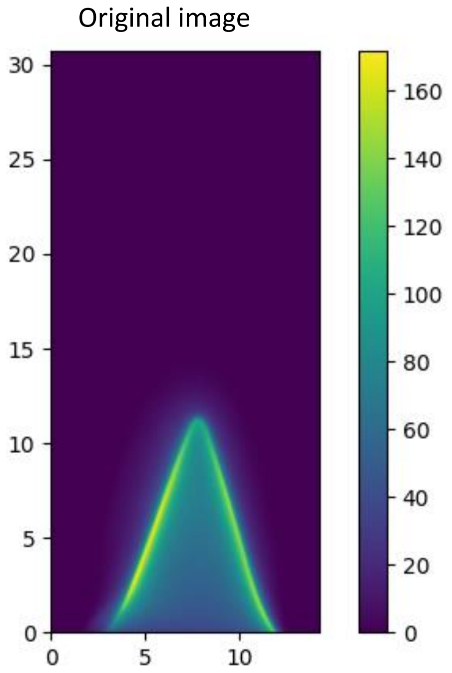


Fig. 8: Flame image from OH chemiluminescence*

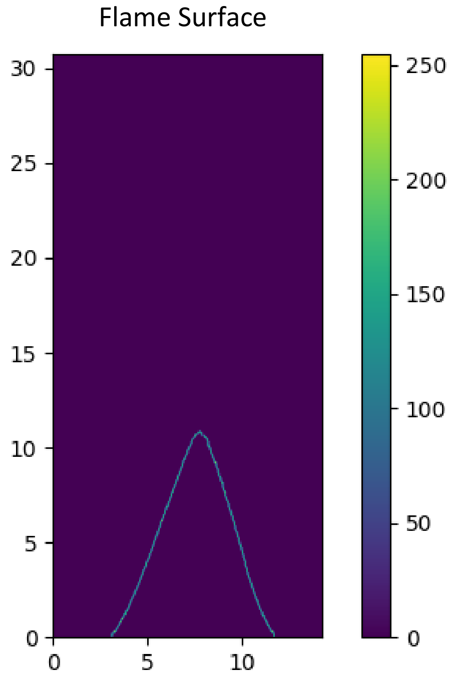


Fig. 9: Extracted flame edge after image processing

A gas probe sampled the gas at the exit of the combustion chamber and the sample was analyzed in an ABB gas analyzer containing URAS (CH_4, CO, CO_2), LIMAS (NO, NO_2) and Magnos (O_2).

The laminar burning velocity (LBV) was measured for the various fuels produced during this project and benchmarked against the values for Jet-A1. The experiment was done with the final PUREJET sample (PJF12) and was tested in blended form of 10% and 20% (labelled as SAF_10 and SAF_20 respectively in the plots). The resulting LBV values are shown in Fig. 10. The values are very similar to those of JetA1, however, the curves are left-shifted along the equivalence ratio axis for the SAF blends. As the equivalence ratios were set based on massflow values for JetA1, this indicates a shift in molecular formula from the it. The NOx emissions are shown in Fig. 10 and the values are close in magnitude, however, the SAF blends show higher values, by ~20ppm at equivalence ratios 0.9 and 1.0. The reason behind this higher NOx level is not known but we hypothesize that a higher C/H ratio in the SAF may lead to product gases with lower specific heat capacity (as more CO2/H2O). For an equal heat release, this would lead to higher flame temperatures, leading to higher NOx. However, it should be noted that this experiment has a much longer residence time, O(s), compared to gas turbine engine combustors, O(1e-3 s), and thus limiting the actual NOx produced in practical devices.

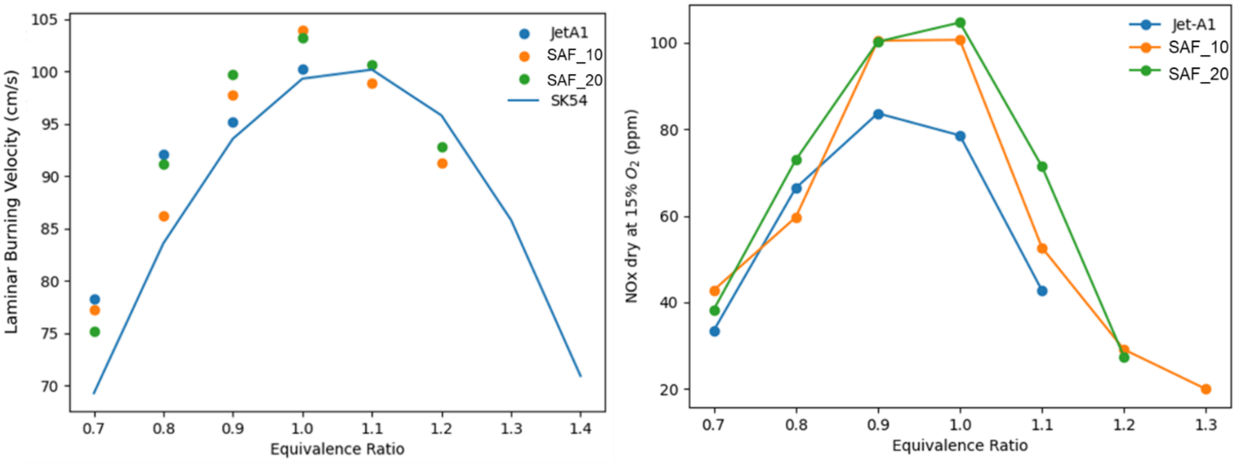


Fig. 10: Laminar Burning velocity

PUREJET (blends) testing in a microgas turbine engine

The final PUREJET fuel sample, blended with JetA1 was tested in a microgas turbine setup with the objective of measuring emissions and performance and comparing them against those obtained while running it on Jet-A1. The experiments were done on the MiniLab Gas Turbine Power System, manufactured by Turbine Technologies, Ltd. This is a self-contained jet engine laboratory with an SR-30 turbojet engine. It is instrumented with temperature, pressure, rotational speed and thrust measurement

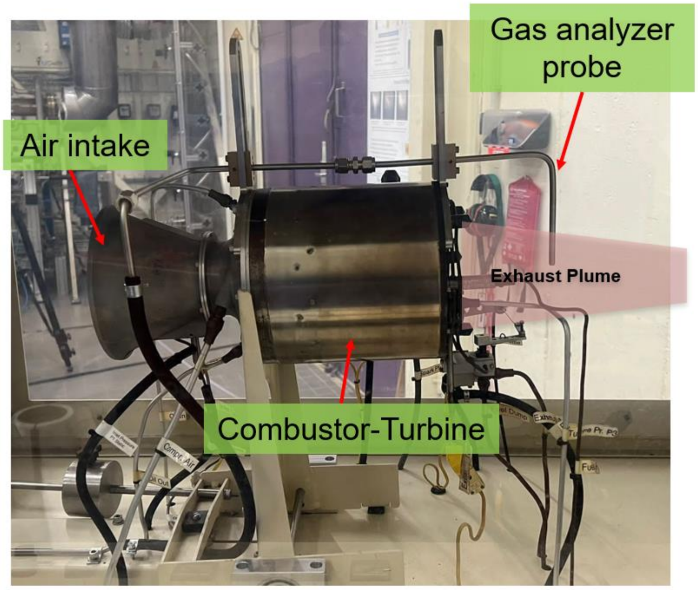
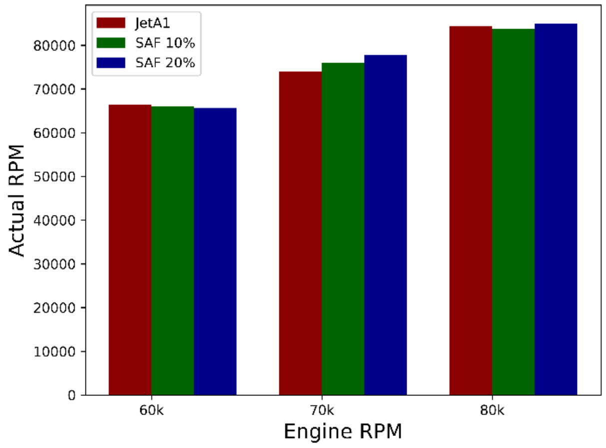
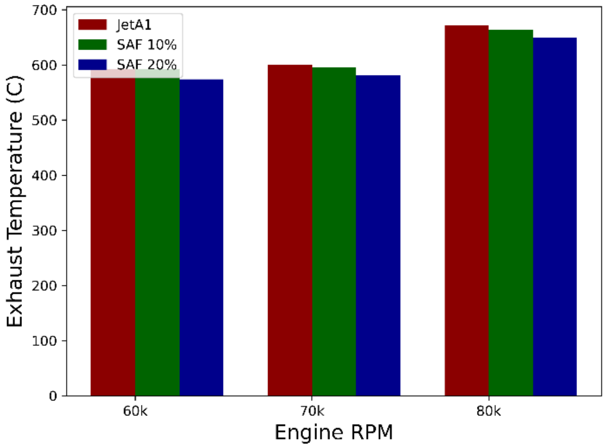


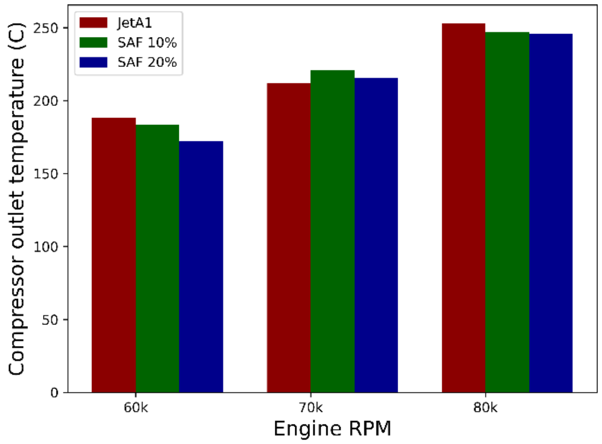
Fig. 11: MiniLab Gas Turbine Power System

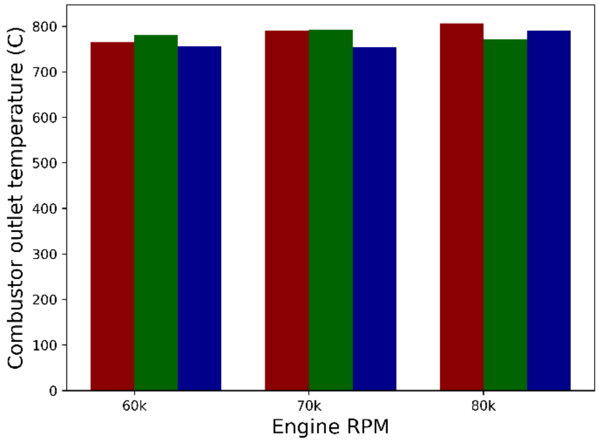
sensor. In addition, a gas-analyzer probe was fitted at the exhaust and a suction based analyzer unit (mentioned earlier) was used to extract and analyze the sample.

The gas turbine was operated at 60k, 70k and 80k rpm for JetA1, 10% SAF blend and 20% SAF blend. The balance in the blend is Jet-A1. The following figures show the performance related quantities measured in the gas turbine. One observes that there is some deviation of the exact rpm from the target value. This is because this is controlled by a manual throttle without a governing system to correct for any deviations. However, for a given engine RPM, the Exhaust, compressor outlet and combustor outlet temperatures are very similar for all fuel samples.

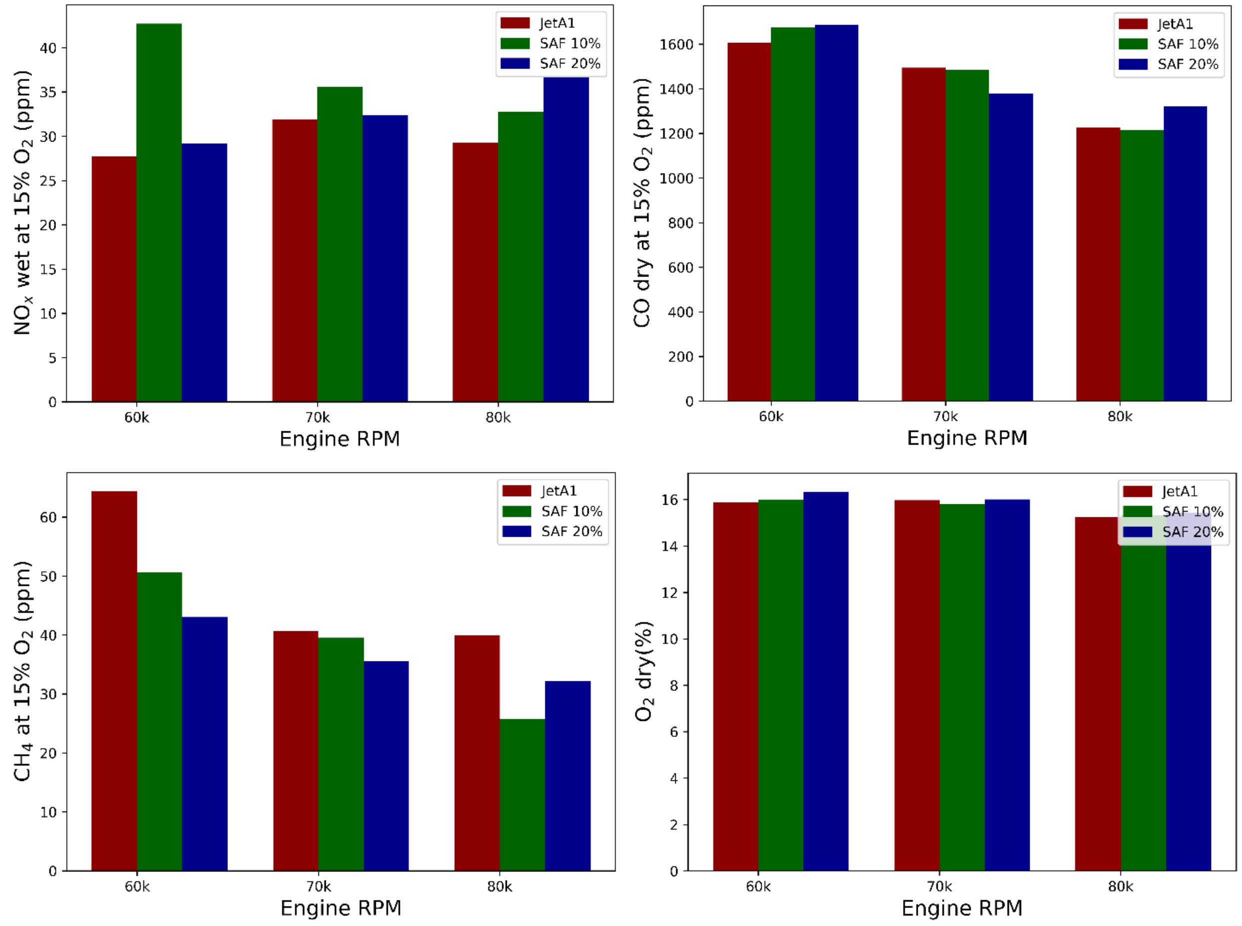








The emissions of NO_x and CO shown in the figures below, are very similar in magnitude for JetA1 and SAF blends. CO has a a systematic decrease with increase in engine RPM which along with a similar trend for CH_4 suggests that the combustion efficiency increase with increase in RPM. It is interesting to note that the NOx emission for 20% SAF have an increase with engine rpm while that for 10% SAF decreases.



Sustainability of the PureJet value chain

Obviously, to qualify as a Sustainble Aviation Fuel it is important that a significant GHG emission reduction is achieved and a minimum value of 65% is assumed. Values of over 70% are achievable with PureJet and mainly depend on the individual contributions of the main feedstocks (pyrolysis oil and hydrogen). In particular, the source of hydrogen is crucial. The preferred route is the internal production of hydrogen or hydrogen from renewable power.

Aviation contributes 2.5% of human-made CO2 emissions, but its overall impact on the climate is larger due to non-CO2 effects like contrails and nitrogen oxides. It can even account for two-thirds of aviation global warming effect. Contrails are formed when water vapor freezes around particles (e.g., dust, sand or soot), causing a visible line-shaped condensation trail (contrail), which can persist from minutes to hours depending on temperature and humidity. Contrails have an immediate warming effect by trapping heat in the lower atmosphere.

Fuel composition has an impact on the persistence of contrails, in particular related to the formation of soot particles. Aromatics, specifically naphthalene, contribute significantly to soot particle formation, whilst pure paraffinic fuels cause fewer soot particle formation. Generally, sustainable aviation fuels (SAF) jet fuel blends have lower aromatics content compared to Jet-A1. While a minimum aromatics content is currently required for seal swelling properties, this may change with future developments.

PureJet has an aromatic content between 5-15%, it mainly consists of cyclo-alkanes and typically does not contain any di- and tri-aromatics like naphthalene. The replacement of aromatic components by cycloalkanes might be beneficial for fuel performance and reducing emissions. Discussions are on-going on the further reduction of aromatics in jet fuel and whether a lower minimum value can be acceptable. High cycloalkane fuels like HPO-Jet may play and important role in that, but more research on these high cyclo-alkanes fuels and its combustion performance and soot formation are needed.

Market perspective of the PureJet product

Within the PureJet project, SkyNRG assessed the market readiness of the PureJet product by contributing to WP 3 Value chain assessment and market perspective in which SkyNRG led Task 3.2 Market perspective of the PureJet product. The objective of Task 3.2 is to provide a market perspective of the PureJet product by (1) evaluating the technical readiness of the PureJet product as a drop-in SAF using existing fuel quality specifications and (2) determining the market potential for the SAF product in relation to the industry benchmarks to help develop the implementation strategy for the value chain.

Commercial aviation fuels must comply with stringent quality specifications set by ASTM. PureJet-SAF is evaluated using ASTM fuel specifications and compared to other approved SAFs and conventional jet fuel to assess the product suitability and its potential to become an ASTM qualified SAF production pathway. PureJet samples were produced by BTG throughout the project and tested for hydrocarbon composition, bulk and physical properties, and trace components. Therefore, evaluation of the fuel product quality also occurred via an iterative process. In total four representative samples—Jet 6, Jet 7, BTG-4306, and BTG-4833—are used in SkyNRG's evaluation of the PureJet product quality. These samples were produced at different stages of the project, allowing direct feedback on test results and process performance to improve both fuel quality and the accuracy of subsequent test results going forward.

In the preliminary analysis of Jet 6 and Jet 7, it was noted that some key properties were missing or tested via undesired test methods. As a result, limited and inaccurate insights into fuel quality arise. For example, GC-VUV was performed to measure hydrocarbon composition, yielding an abnormal hydrocarbon distribution of Jet 6 & 7. As the analysis of the test results demonstrated some unexpected, non-linear, behavior it was recommended to verify these results by using GC×GC instead. The results revealed a more natural and reliable hydrocarbon composition and distribution in these and subsequent samples. Also, it was recommended to perform tests on properties such as thermal stability, flash point, and existent gum to get more insights on the performance and stability of the fuel. Accordingly, the testing of later samples BTG-4305 and BTG-4833 gave more comprehensive insights and conclusions on PureJet fuel quality.

The fuel evaluation results showed very promising results for large scale uptake of PureJet fuels. The evaluation concludes that PureJet-SAF has a higher cycloparaffin content (>75% wt) than conventional jet fuel, resulting in a distinct hydrocarbon composition compared to conventional jet fuel or other approved SAF. Nevertheless, the fuel exhibits many characteristics that make it suitable for qualification with high blending percentages. This is particularly true for the final sample BTG-4833, which demonstrated compliance with all critical SAF specifications and appears suitable for safe operations in commercial aviation and ready for ASTM qualification.

Based on the fuel quality data obtained during the PureJet project, it is recommended that PureJet pursues ASTM qualification through the standard ASTM D4054 evaluation procedure, aiming for approval at the highest possible blend percentage. Although the final sample (BTG-4833) yielded very promising results, variations in fuel properties were observed among the various samples, despite similar processing conditions. Issues included failure to meet acidity, gum formation, and viscosity requirements in some cases. Additionally, while some samples had a freezing point consistent with Jet A, others were unable to meet Jet A-1 requirements. It is recommended to address these product variations prior to entering the qualification process, so that fuel samples during the ASTM process are considered representative and reliable for commercial operation. Furthermore, it is recommended to gain a better understanding of the natural variability of the process and product based on envision feedstock sources, along with a clear vision on the commercialization strategy to help mitigate potential issues during qualification. It is therefore recommended to resolve these discussions points prior to initiating the ASTM qualification procedure. Meanwhile, BTG initiated the production of new Jet samples to show that the high quality jetfuel can be reproduced and that the final PureJet sample is representative.

Overall, the quality assessment of PureJet confirmed a high-quality jet fuel product suitable for commercial aviation and identified the need for the technology to mature into a controlled and stable production process. The chemical confirmation of a high-quality product is in line with the combustion results by TUD showing no significant NOx emission differences between PureJet & conventional jet fuels.

The second part of Task 3.2 is to investigate and advise on the market potential of PureJet. To do this, future SAF supply and demand have been investigated to determine interesting market segments where PureJet can serve its role in decarbonization of the aviation sector. Taking into consideration SAF mandates, incentives, targets, and sustainability requirements in different regions around the world, it was concluded that the largest opportunity for pyrolysis pathways is in the European mandated SAF market from 2035 and onwards. The market opportunity for pyrolysis SAF is expected to be created by long-term SAF demand certainty realized by the ReFuelEU mandate and its strict sustainability requirements for SAF. Due to the limited availability of waste oils and fats, meeting the EU mandated demand requires the production of advanced biofuels from 2035 and onwards.

Today, there are two alternative pathways to produce advanced bio-SAF: the Fischer-Tropsch process and the alcohol-to-jet process. The rollout of these pathways has been partly limited due to technological issues, creating a significant market opportunity for new advanced bio-SAF routes. PureJet technology is robust and has demonstrated its capability to produce high-quality SAF. Combined with the economic performance of the pathway, there is strong potential for the PureJet pathway to capture a significant share of the advanced bio-SAF market.

In other global markets, the potential for pyrolysis depends on regional policy developments. Policy certainty and sustainability requirements vary across regions and differ from those of the EU. This variability affects business stability, and sustainability requirements on feedstocks may also vary. These factors influence the demand for advanced bio-SAF and affect their economic viability in these markets.

In summary, the results of Task 3.2 have demonstrated the potential for PureJet SAF to become a commercial SAF production pathway with possibilities to roll out and penetrate the European SAF market from 2035 onwards.

Main conclusions

Fast pyrolysis bio-oil has been successfully upgraded and -after distillation- a high quality, colorless, cyclo-alkane rich jet-fuel was obtained. The jet-fuel was analyzed extensively and compared to existing ASTM specifications, and for all measured properties the PureJet fuel did comply with the specifications. Compared to Jet A1 the PureJet fuel has a higher density, and as a result a higher volumetric energy density. The Carbon Number distribution of JetA1 and PureJet are quite comparable, but significant differences exist in the composition. Jet A1 contain comparable amounts of n-, iso and cycloalkanes whereas PureJet consists primarily of cyclo-alkanes. The aromatic content in Purejet depends on the severity of hydrotreatment and olefins are virtually absent.

The PUREJET fuels (blends) combustion characteristics were tested on a fundamental level in a premixed-prevaporised Bunsen burner setup and on an applied micro gas turbine engine. Values of laminar burning velocity and NOx emissions from the Bunsen flame are similar in magnitude to those for JetA1, however for certain equivalence ratios slightly higher NOx was observed for the SAF blends than JetA1. In the micro gas turbine engine tests, similar magnitudes of NOx and CO emissions were measured for SAF blends and JetA1, with deviations of <15ppm of NOx from the values of JetA1.

GHG emission reduction values of over 70% are achievable with PureJet. To achieve high values in particular the source of hydrogen is crucial. The preferred route is the internal production of hydrogen and further assessment of potential options is recommended. PureJet may have a positive effect on non-CO2 impact of aviation fuels as cyclo-alkanes may partly replace aromatics, but dedicated research on combustion of cyclo-alkanes would be needed for quantification.

Based on a detailed analysis of the Purejet fuel properties and a market assessment, the potential for PureJet has been demonstrated to become a commercial SAF production pathway with possibilities to roll out and penetrate the European SAF market from 2035 onwards. Repeating the production of the jetfuel is recommended to show that the final, high-quality Purejet sample is representative for the value chain.

Annexes Public

Sustainable Aviation and Marine Fuel from fast pyrolysis bio-oil, Bert van de Beld 32nd European Biomass & Exhibition Conference, Marseille, 2024 (Plenary presentation)

Deel 3: Uitvoering van het project

- *Problemen (technisch en organisatorisch) die zich tijdens project hebben voorgedaan en oplossing.*
  Op hoofdlijnen is het project uitgevoerd zoals beschreven in het projectvoorstel. Op basis van de verkregen tussentijdse projectresultaten zijn er wel wat accentverschuivingengen geweest op detailniveau. Een voorbeeld hiervan is dat er meer aandacht is gegaan naar de analyse van de verkregen brandstoffen en relatief minder naar de verdere opzuivering van het product. Dit kwam ondermeer doordat eerder dan verwacht een hoogwaardige brnadstof kon worden gemaakt.
  Een aantal activiteiten van de TUD zijn in de beginperiode van het project vertraagd vanwege moeizame levering van specifieke onderdelen van de testopstelling. Dit is ook toegelicht in de 1e jaarrapportage. Uiteindelijk heeft dit niet tot problemen geleid bij de uitvoering van het project.

- *Toelichting op wijzigingen tov projectplan*
  Inhoudelijk zijn er geen grote aanpassingen geweest bij de uitvoering van het project. De TUD heeft niet alle opstellingen gebruikt zoals oorspronkelijk voorzien, maar daarentegen zijn andere opstellingen (zoals de lab-scale gas turbine) meer intensief gebruikt. De wijzigingen in de uitvoering hebben geen impact op het overall projectresultaat.

- *Verschillen tussen begroting en werkelijk gemaakte kosten*
  Zoals hierboven aangegeven is er meer budget besteed aan externe analyses dan oorspronkelijk begroot. Dit is in jaarrapportage 2 ook toegelicht. Het heeft geen invloed op het totale budget.

- *Wijze van kennisverspreiding*
  De tussentijdse resultaten van PureJet zijn in 2024 gepresenteerd op de Europese biomassa conferentie (EUBCE2024, plenaire presentatie). Een abstract is geaccepteerd voor een presentatie op het 1e ICSAR congres (International Conference on Sustainable Aviation Research). Dit vindt plaats in juli in Dublin.

- *Toelichting PR project en verdere PR-mogelijkheden.*
  Er zijn op dit moment geen specifieke PR activiteiten anders dan kennisverspreiding.

Annexes – Confidential

A. WP1: Production & analysis of HPO-Jet (BTG).

B. WP2: Combustion Characterization of fast pyrolysis bio-oil derived jet fuels

C. WP3: Non-CO2 emissions & contrails (BTG).

D. WP3: Market perspective of the Purejet product (SkyNRG)

Sustainable Aviation and Marine Fuel from fast pyrolysis bio-oil

biomass technology group

www.btgworld.com

Bert van de Beld

EUBCE 2024

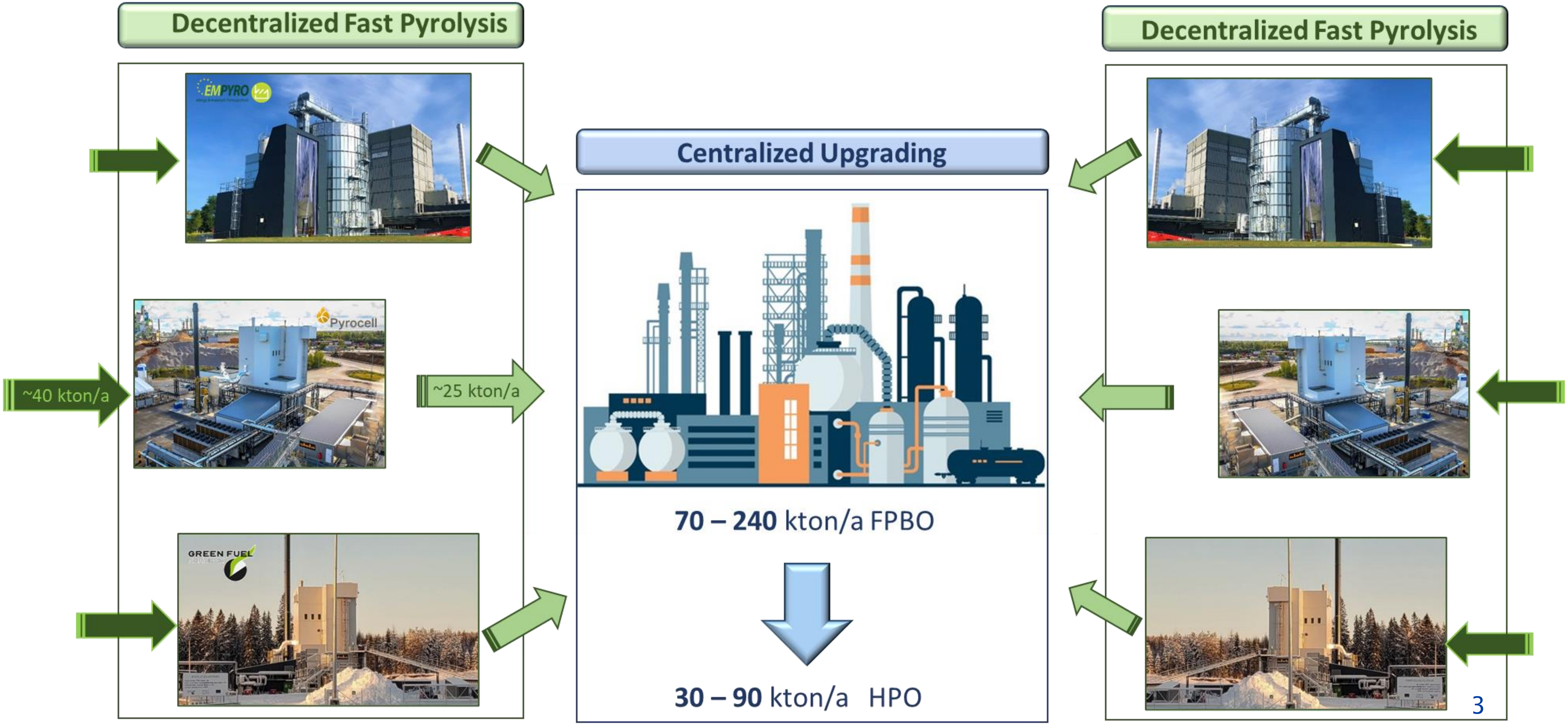
32nd European Biomass Conference & Exhibition

24-27 June | Conference & Exhibition
28 June | Technical Tours
Marseille

Content

- Fast pyrolysis & upgrading – concept
- Pyrolysis oil upgrading
    - Challenge
    - Approach
    - ‘*Dacia*’- process
- HPO-Jet (SAF)
- HPO Marine Fuel
- Summary

Fast Pyrolysis & upgrading - Spoke & Hub model



Decentralized Fast Pyrolysis

~40 kton/a

~25 kton/a

Centralized Upgrading

70 – 240 kton/a FPBO

30 – 90 kton/a HPO

Decentralized Fast Pyrolysis

FPBO = **F**ast **P**yrolysis **B**io **O**il

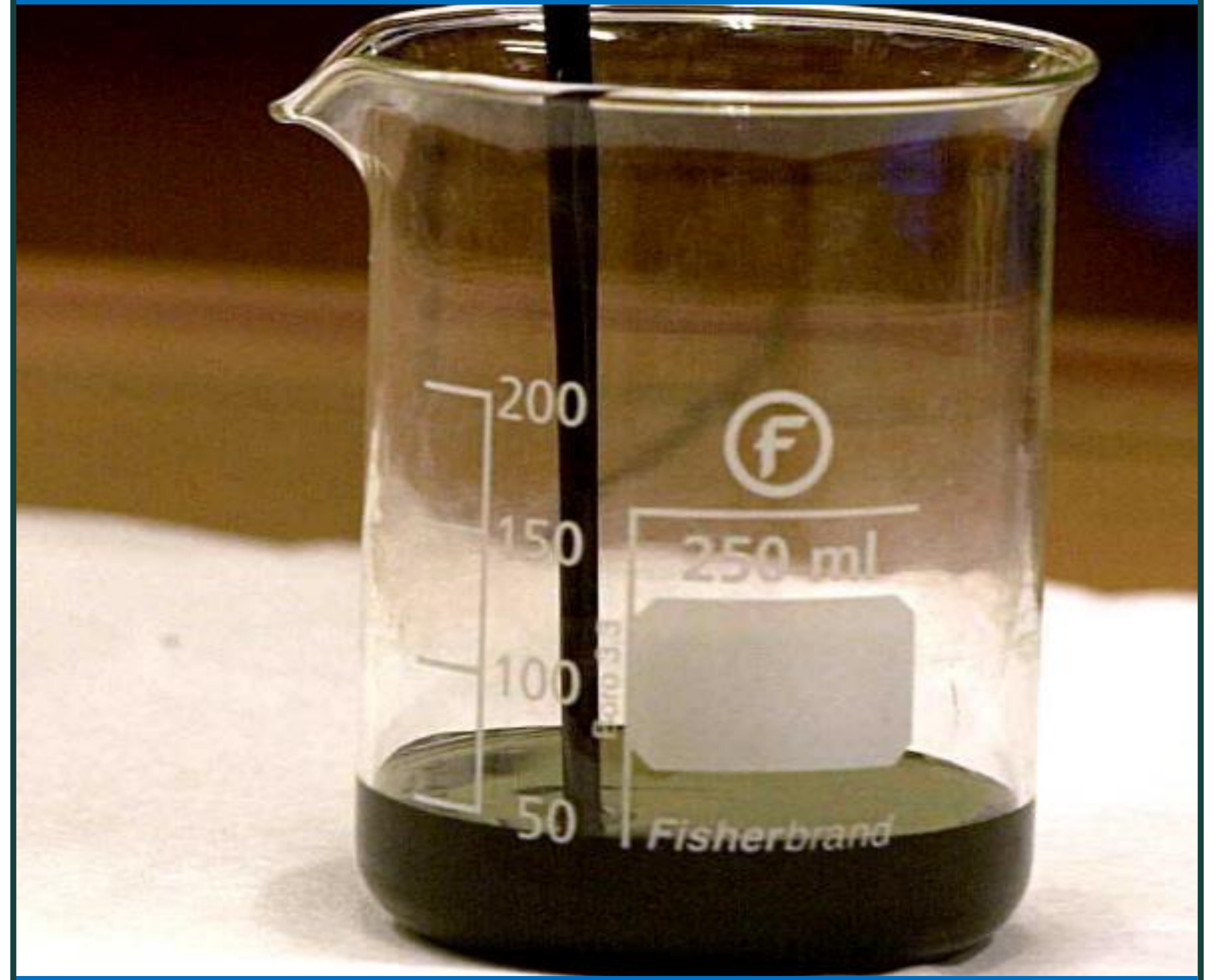
HPO = **H**ydrotreated **P**yrolysis **O**il

The challenge …

Fast Pyrolysis Bio-Oil

Water content	25	wt%
Density	1,170	kg/m^3
LHV	16	MJ/kg
Acid Number	70	mg_{KOH}/g
Sulfur	< 500	ppm
FlashPoint	?	°C
Cetane Number	< 20	-
MCRT	> 15	wt%

Components: Acids, carbohydrates, ketones, aldehydes, water, phenolic,..



Fast Pyrolysis Oil - **FPBO**

Drop-in Fuels

Water content	< 0.008	wt%
Density	< 840	kg/m^3
LHV	> 42.8	MJ/kg
Acid Number	< 0.015	mg_{KOH}/g
Sulfur	< 15	ppm
FlashPoint	> 38	°C
Cetane Numbe	> 35	-
MCRT	<< 1	wt%

Components: hydrocarbons

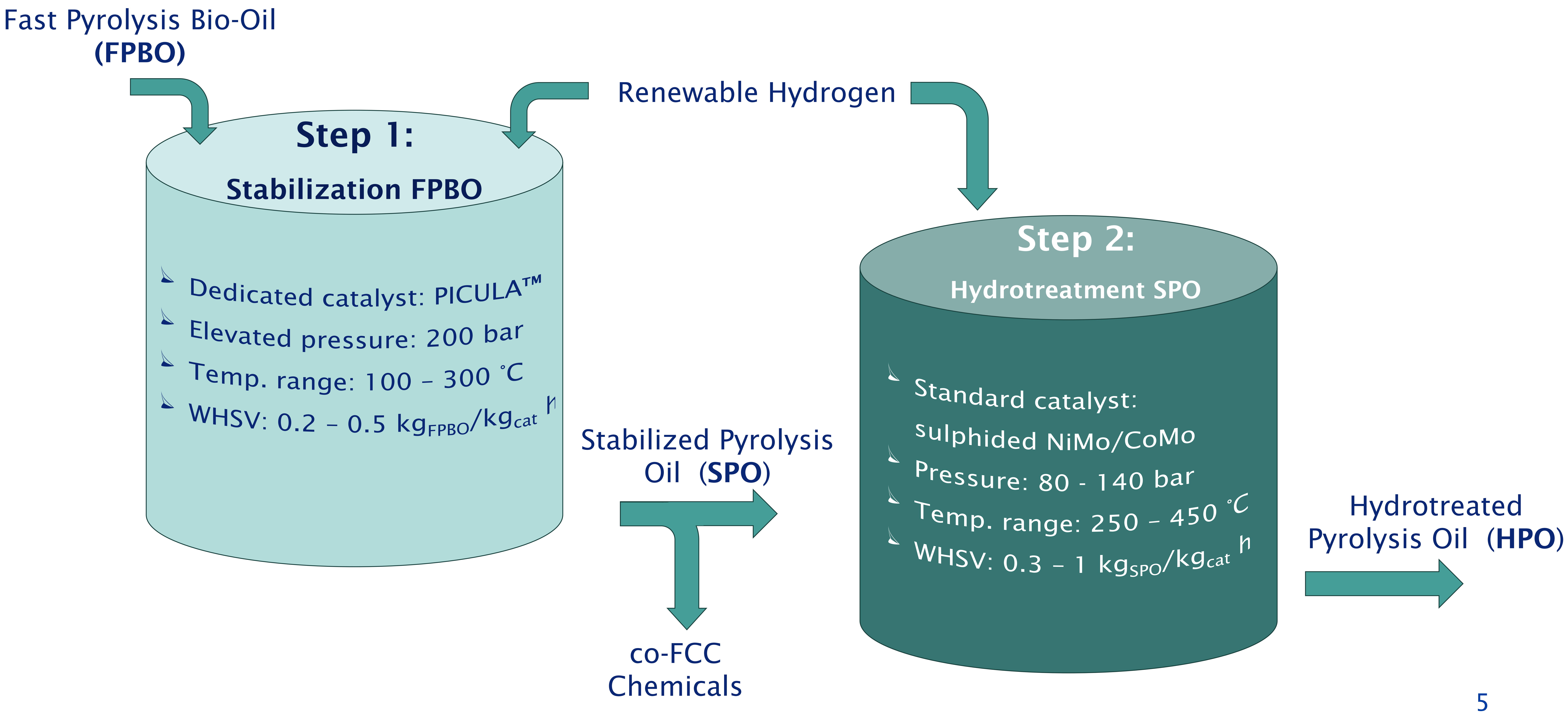
Aviation Fuel – JET A/A1

Water content		wt%
Density	< 890	kg/m^3
LHV	~42	MJ/kg
Acid Number	< 0.5	mg_{KOH}/g
Sulfur	< 1,000	ppm
FlashPoint	> 60	°C
Cetane Numbe	> 40	-
MCRT	< 0.3	wt%

Components: hydrocarbons

Distillate Marine Fuel – DMA

Upgrading approach



Fast Pyrolysis Bio-Oil
(FPBO)

Renewable Hydrogen

Step 1:

Stabilization FPBO

- Dedicated catalyst: PICULA™
- Elevated pressure: 200 bar
- Temp. range: 100 – 300 ˚C
- WHSV: 0.2 – 0.5 kg_{FPBO}/kg_{cat} h

Stabilized Pyrolysis Oil (**SPO**)

co-FCC
Chemicals

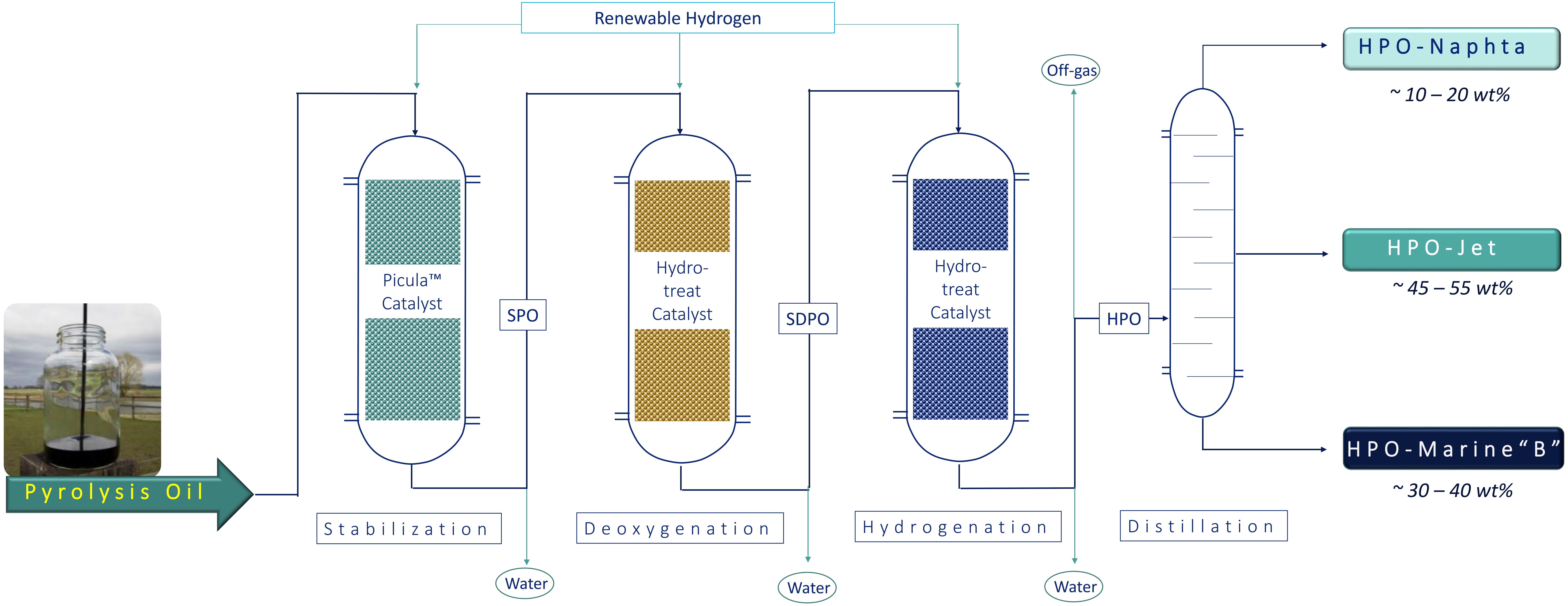
Step 2:

Hydrotreatment SPO

- Standard catalyst: sulphided NiMo/CoMo
- Pressure: 80 - 140 bar
- Temp. range: 250 – 450 ˚C
- WHSV: 0.3 – 1 kg_{SPO}/kg_{cat} h

Hydrotreated Pyrolysis Oil (**HPO**)

Fast pyrolysis oil upgrading – “*the DACIA process*”



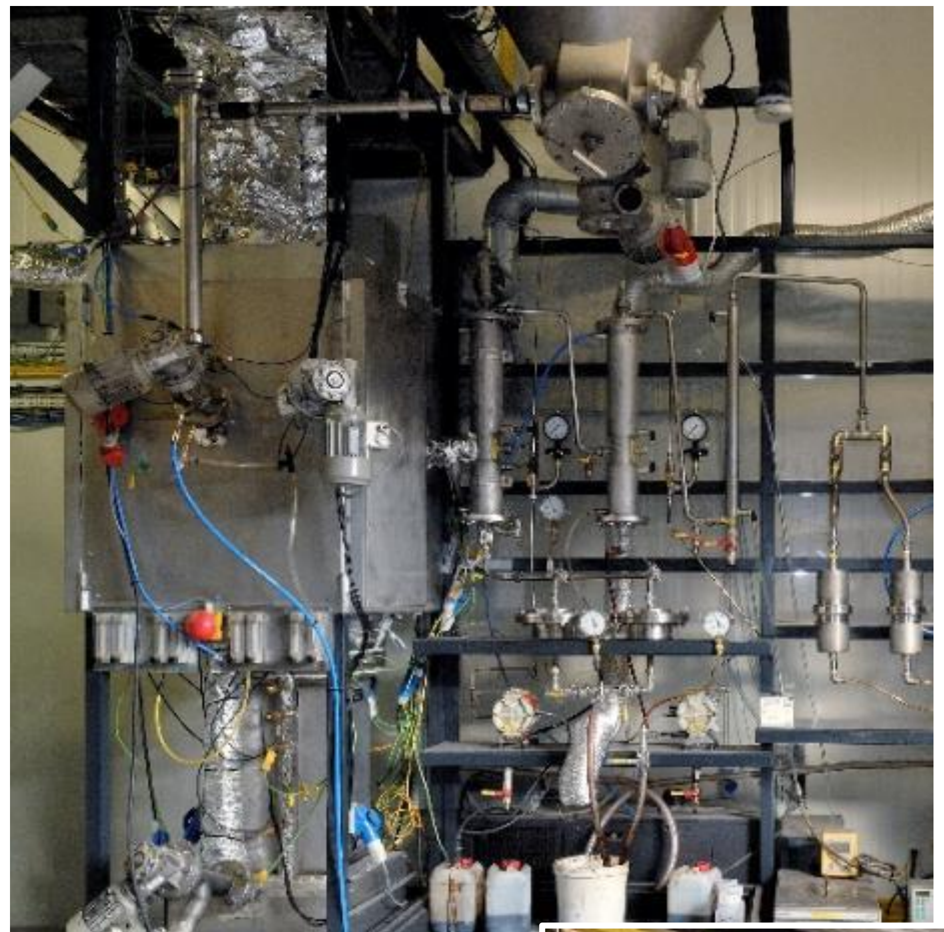
FPBO = Fast Pyrolysis Bio-Oil **SPO** = Stabilized Fast Pyrolysis Oil **SDPO** = Stabilized Deoxygenated Pyrolysis Oil **HPO** = Hydrotreated Pyrolysis Oil

⚠ HPO Marine “B” is recovered from higher quality HPO than Marine”A” as such high quality is needed for the HPO-Jet fraction

Fast pyrolysis oil upgrading – “*the DACIA process*”

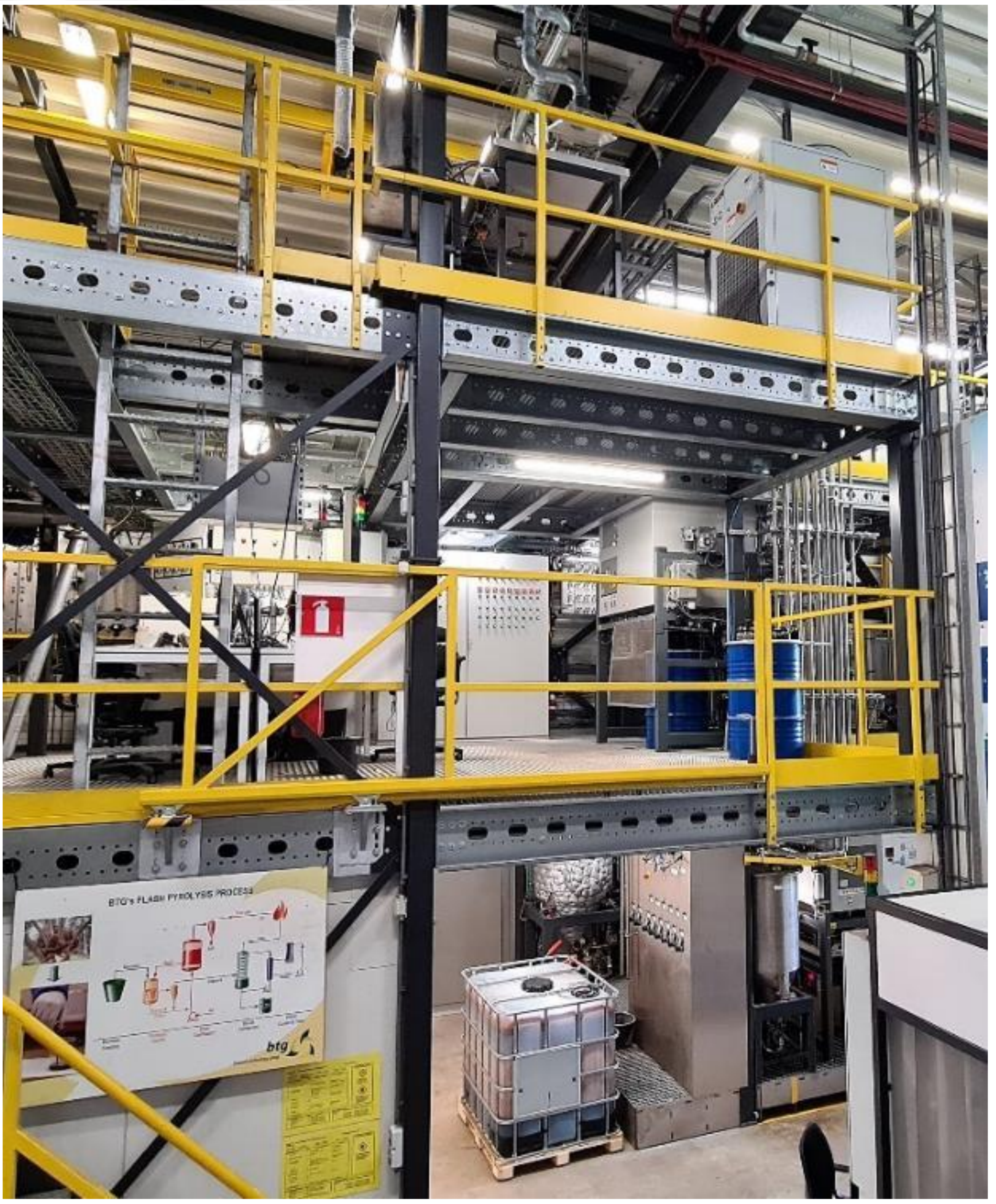
Test Facilities “Biomass to Advanced Biofuels”

Biomass



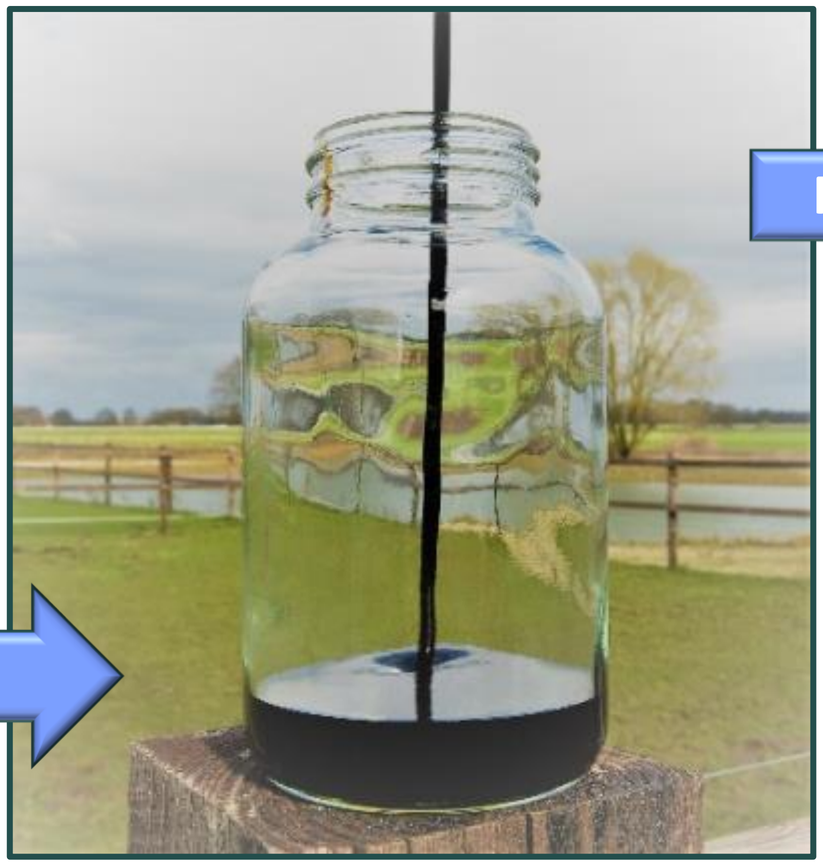
Bench-scale fast pyrolysis
- 2-4 kg/h
- Day operation – typical 2 -4 h runs

Bench- & pilot scale fast pyrolysis test facilities



Fast Pyrolysis Pilot Plant
- 100 – 200 kg/h
- Day operation – typical 4 -10 h runs

FPBO

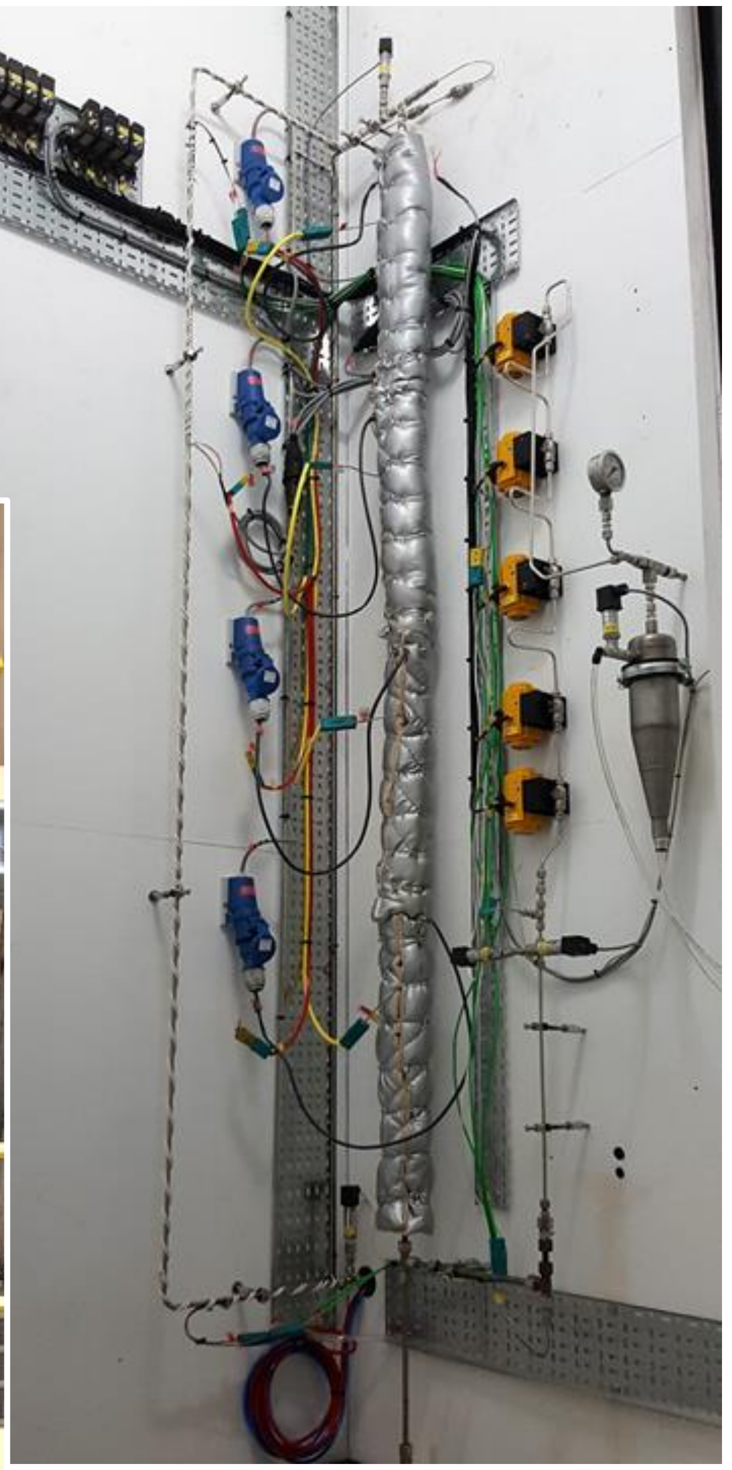


FPBO

Hydrogen from AEM -Electrolyser.

H2

Bench- & pilot scale hydrotreating facilities



Benchscale hydrotreaters (5 units):
- 0.5 – 1.5 kg feed/day
- 24/7 operation
- Cumulative > 25,000 h

Pilot-scale
- 20 – 50 kg feed/day
- 24/5 operation
- Cumulative > ~5,000 h

HPO

FPBO upgrading

Stabilization →

Hydrotreatment →

Parameter	Unit	FPBO	SPO	SDPO	HPO
Water content	wt.%	20 - 23	≤ 10	< 2	<0.1
Density	kg/l	1.2	1.1	0.90	0.85
Viscosity (40°C)	cSt	32	100	10	2
Acid number (carboxylic)	mg KOH/g	60 - 70	60 - 70	< 5	<0.03
Carbonyl content	mmol/g	4.5	< 2	< 1	<0.1
MCRT	wt.%	17 -20	≤ 10	< 0.5	0
Carbon content	wt.%	42-44	53 – 58	78 - 83	85.3 – 87.6
Hydrogen content	wt.%	7 - 8	8 – 9	10.5 – 11.5	12.4 -14.7
Oxygen (by difference)	wt.%	47 - 50	30 - 40	4 - 8	< 0.1
Lower Heating Value	MJ/kg	16 – 18	23 - 25	37 - 39	42 - 43
H/C	mole/mole	1.3 – 1.5	1.5 – 1.7	1.6 – 1.7	1.7 – 2
O/C	mole/mole	0.45 – 0.52	0.3 – 0.45	0.03 – 0.05	< 0.01

⚠ *Indicative values*

FPBO = Fast Pyrolysis Bio-Oil **SPO** = Stabilized Fast Pyrolysis Oil **SDPO** = Stabilized Deoxygenated Pyrolysis Oil **HPO** = Hydrotreated Pyrolysis Oil

HPO-JET

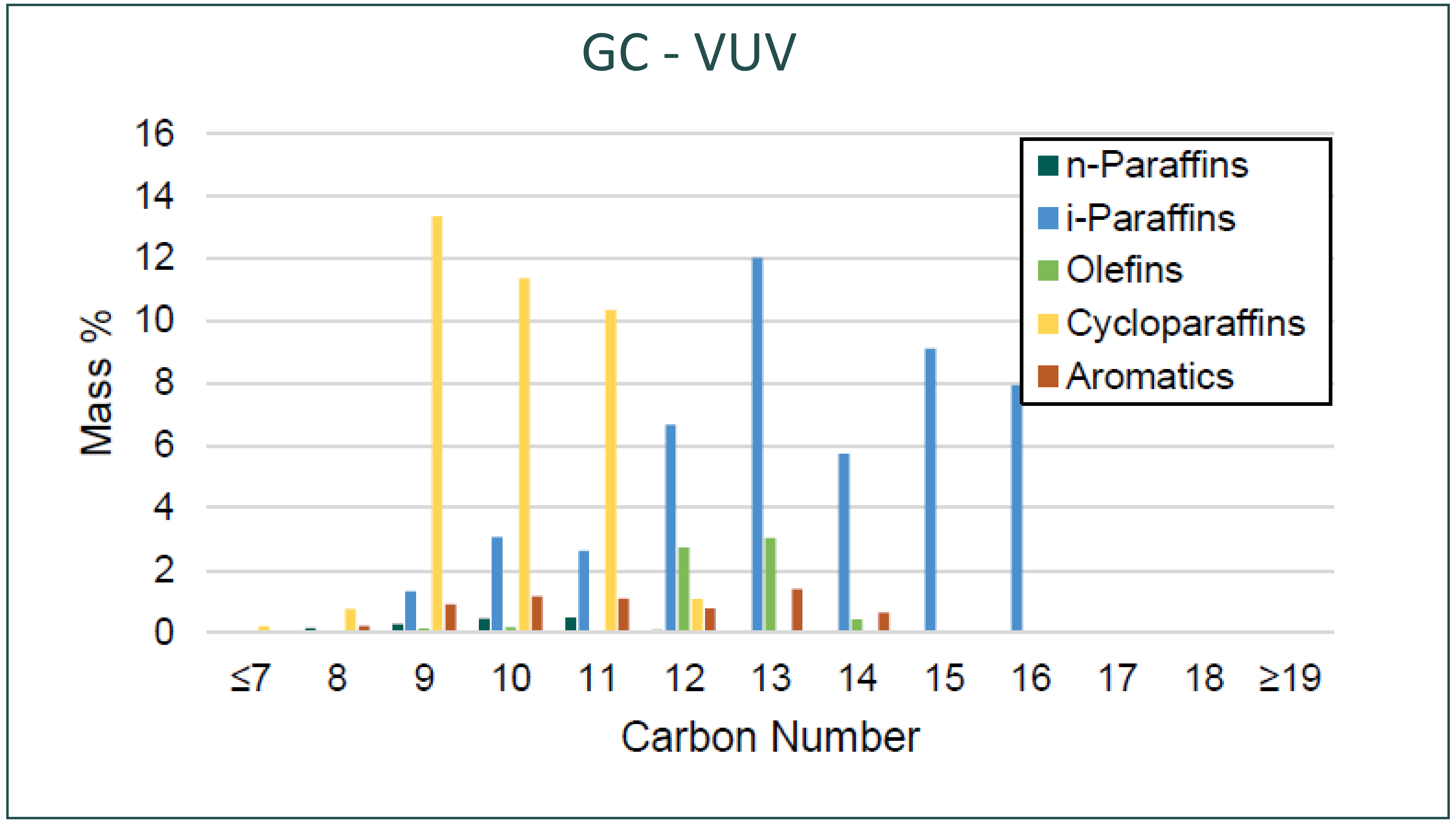
Parameter	Unit	ASTM Specifications			JET-A1	HPO - JET		
		D1655	D7566	D4054	TUD-sample	1	2	3
Density (T = 15 °C)	kg/L	775 - 840		730 - 880		833	831	841
Water	mg/kg			< 75	35	36	25	<30
Viscosity (-20 °C)	cSt	< 8	< 12 (at -40°C)		3.79	5.48	5.42	7.1
Acidity	mg KOH/g	< 0.10		< 0.015	-	0.007	0.003	0.04
Flashpoint	°C	> 38		38 - 66		41.6	46	58
Freeze Point***	°C	< -40 / -47		< -40	-50.9	-41.5	-45.4	-43.1
Net Heat of combustion	MJ/kg	> 42.8		-	43.1	43.0	43.0	43.1
Sulfur content	mg/kg	< 3,000		< 15	846	<5	<5	<1
Nitrogen content	mg/kg			<2	<5	<5	<5	<0.5
Smoke Point**	mm	>25 or > 18 if napthalenes < 3%			25.0	20.9	23.8	22.7
Napthalene	v%							0.09
DCN/ICN	-			35 - 60	47.5	39.6	38.8	43.4
IBP (ASTM D86)	°C			130 – 190	150.8	157	162	160
10% recovered	°C	< 205		150 - 200				178
FPB (ASTM D86)	°C	< 300		195 - 296	265.1	284	280	290
Aromatics	v%	< 25	8 - 25	< 20	16.09	15.09	8.66	10.2
Mono-aromatics	v%				15.23	15.09	8.66	10.2
Diaromatics	v%				0.86	<0.01	<0.01	<0.1
JFTOT (260 °C)*		V		V	V			V

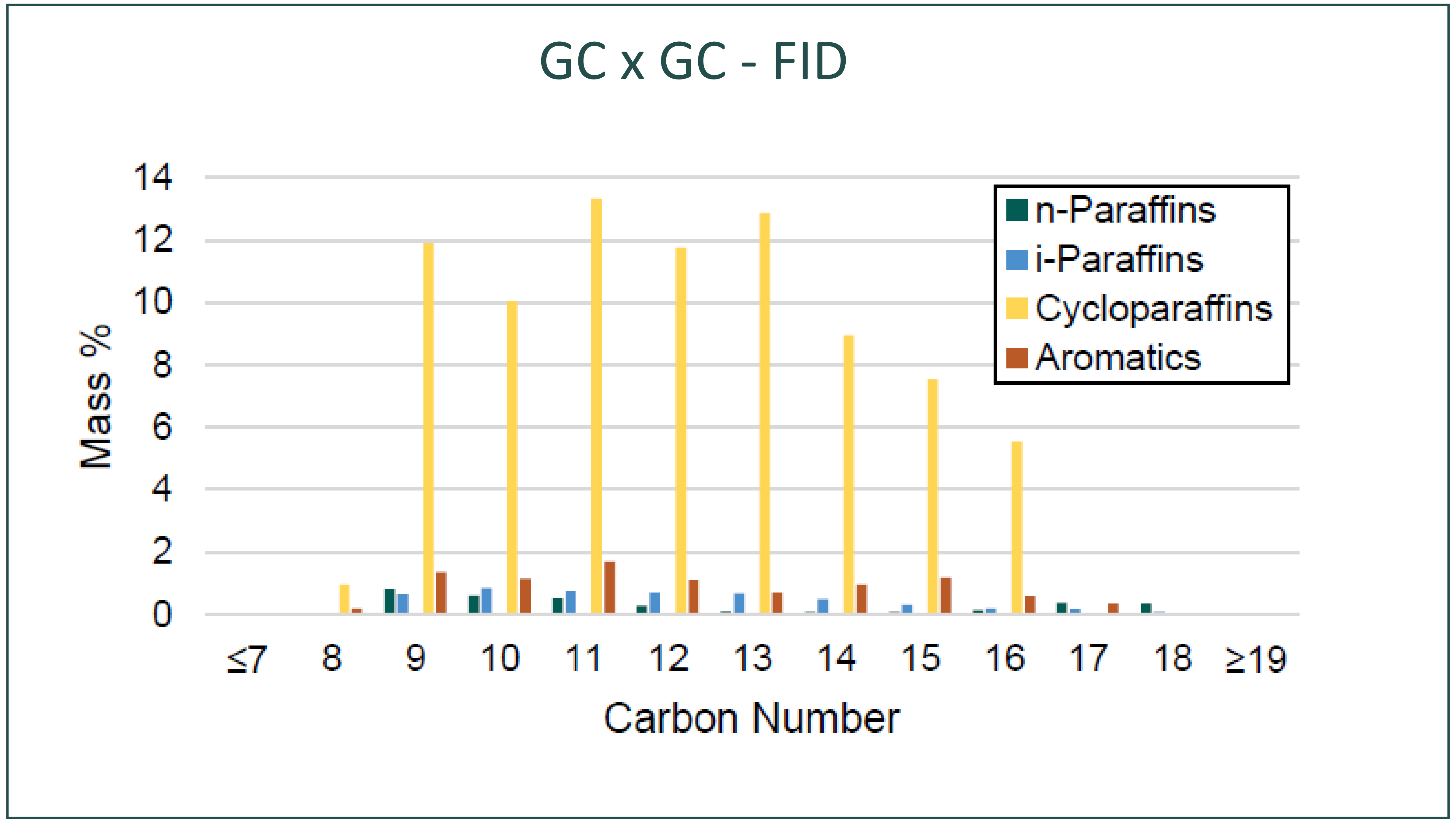
* JFTOT performed for 1 HPO-JET sample at 260 °C (standard), biofuels require 325 °C

** >18 if naphthalene content < 3%

*** Jet A = -40°C; Jet A1 = -47 °C

HPO-JET Composition



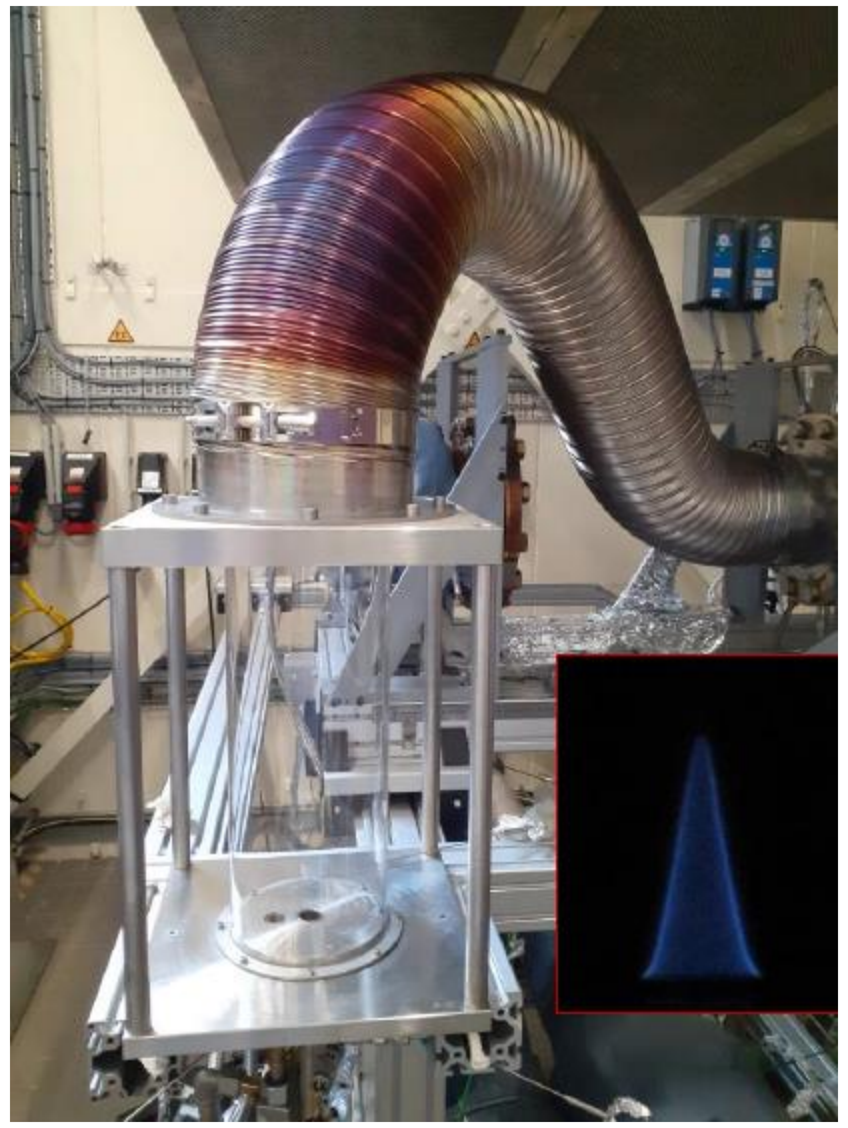


** Both HPO-JET, not exactly the same sample*

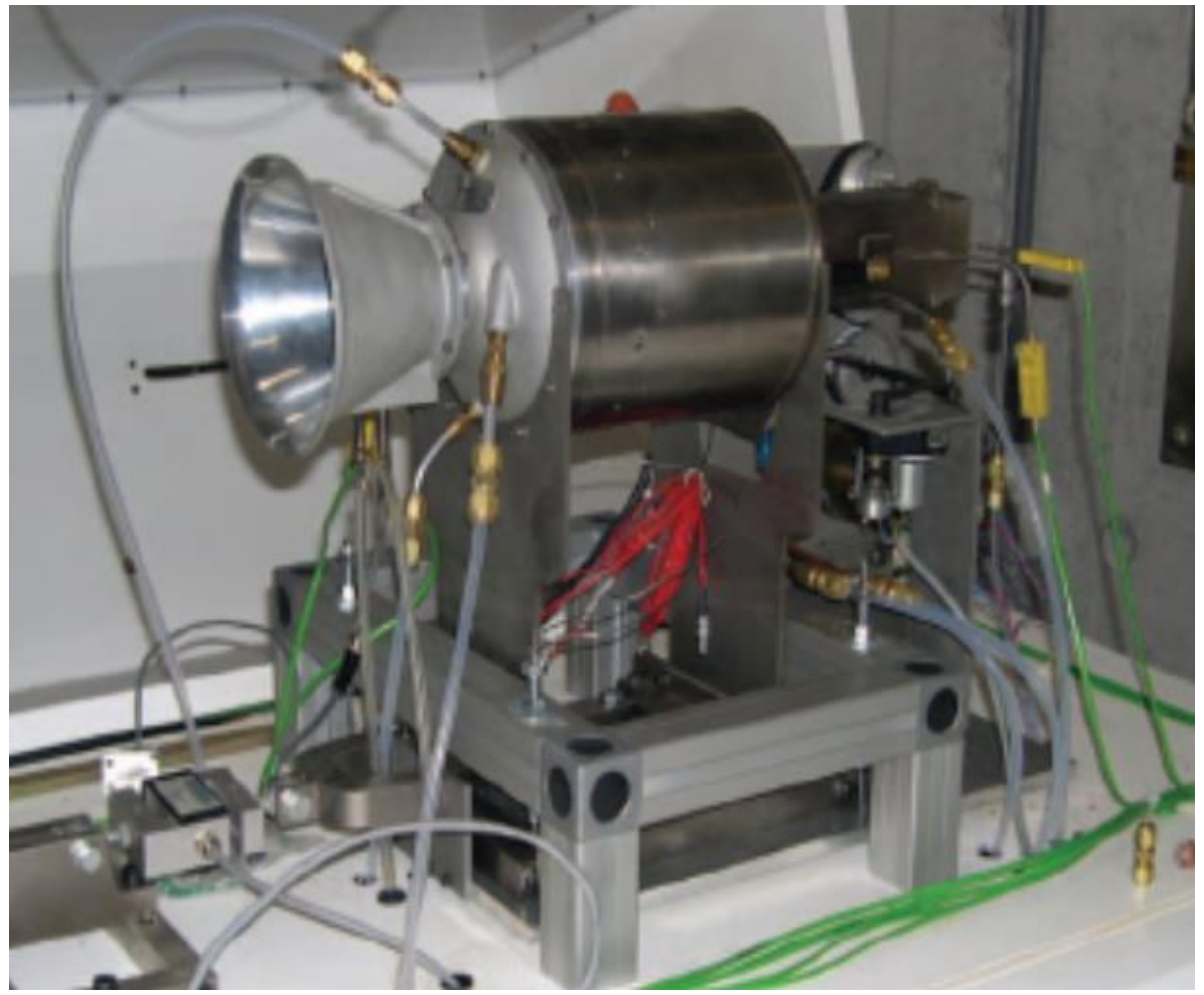
- GC-VUV not reliable for carbon number > 12 (Likely, no olefins and majority iso-alkanes = cyclo-alkanes)
- GC x GC-FID is the ASTM approved method
- HPO-Jet: majority cyclo-paraffins and virtually no olefins.
- ASTM D-4054: * Cyclo-paraffins < 30%
  * Aromatics < 20%

HPO JET fuel – combustion testing

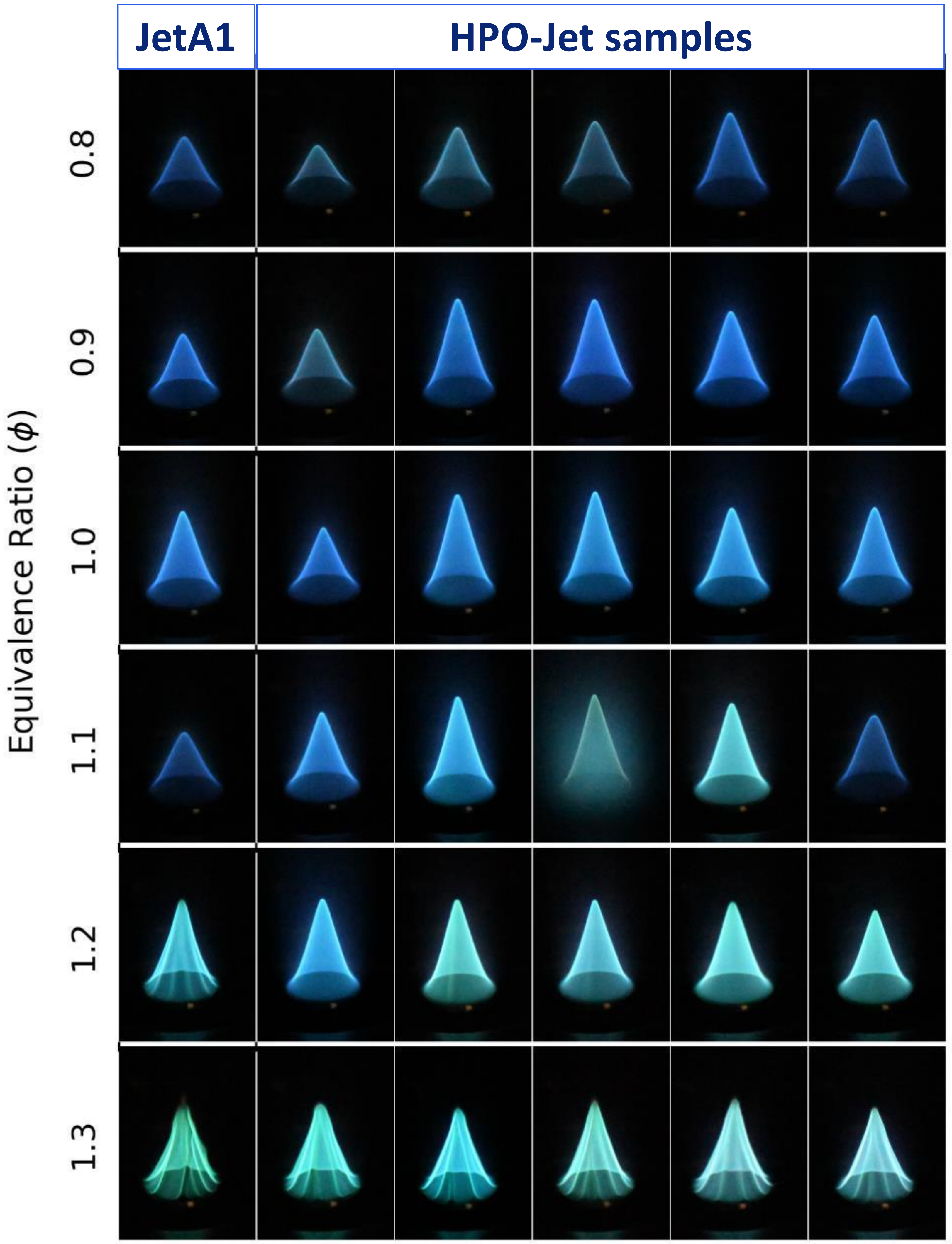
- Comparison Jet-A1 & HPO-Jet
- Experiments at Technical University Delft on-going
  - Laminar flame velocity
  - Fuel atomisation & mixing
  - Lab-scale Turbine test (Q4-24 / Q1-25)



Combustion test set-up at TUDelft



MinLabTM gas turbine from Turbine Technologies Ltd.



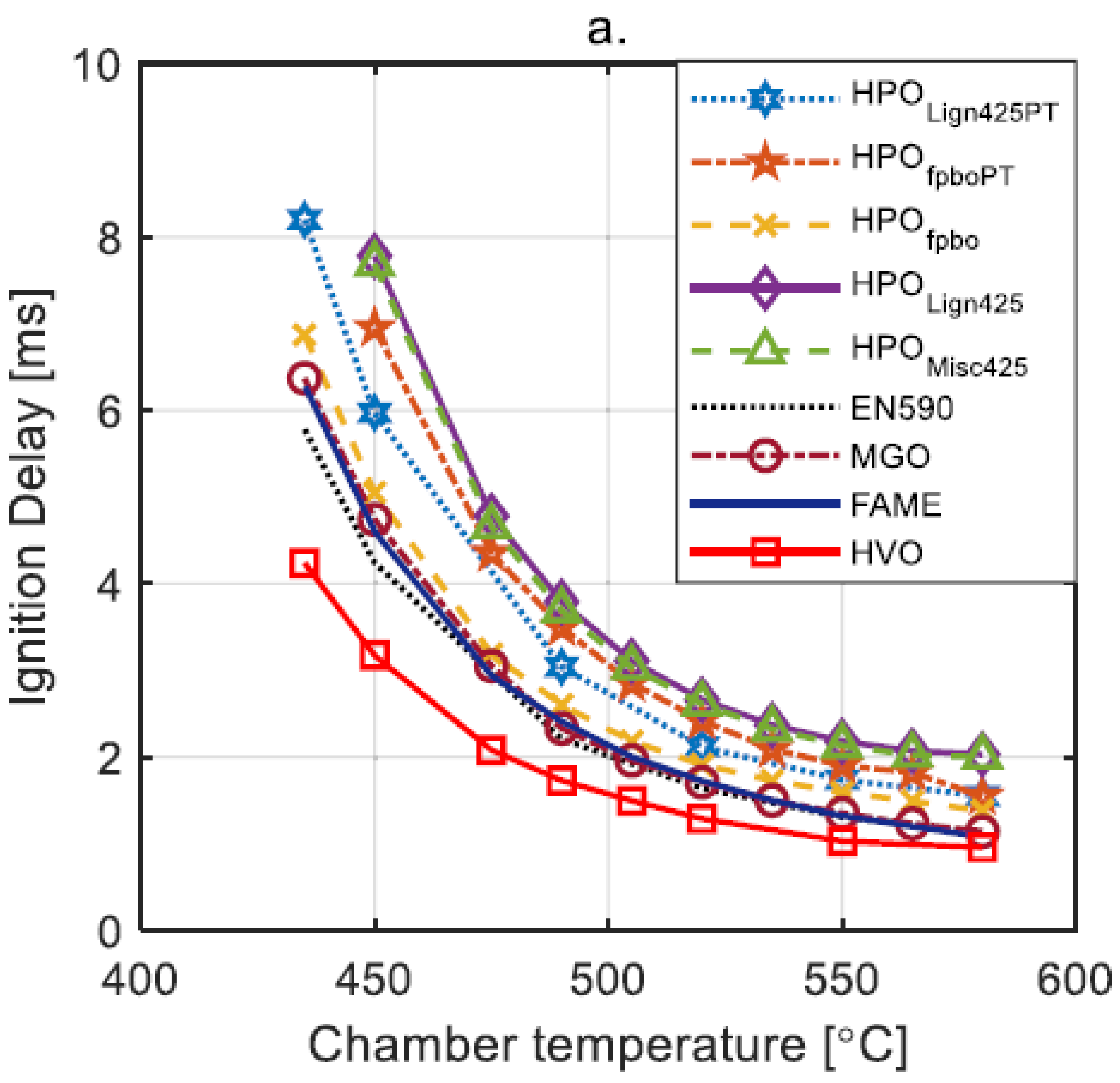
Determination Laminar flame velocity

HPO Marine fuel

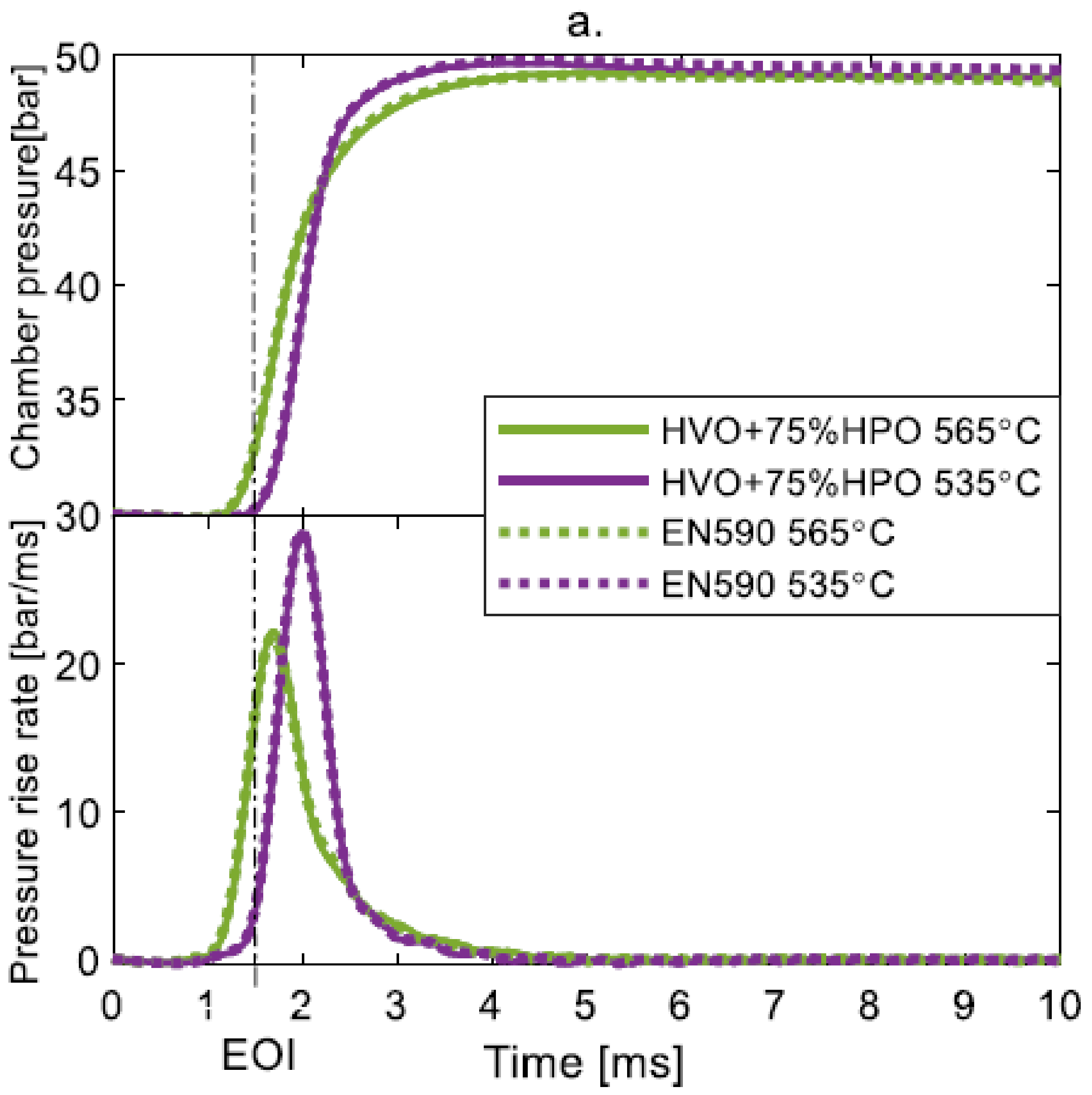
Parameter	Unit	ISO 2817: 2024			HPO - MARINE	
		DMA	DMB	RMA 20	“A”	“B”
Density (T = 15 °C)	kg/m^3	< 890	< 900	< 955	891	909
Viscosity (40 °C)	cSt	2 - 6	2 - 11	2 -20 (50°C)	3.3	15.8 (50°C)
Acidity	mg KOH/g	0.5	0.5	2.5	<0.01	0.12
Flashpoint	°C	60	60	60	60	171
IBP	°C				> 170	> 300
Cloudpoint	°C	report	report		-26	-26
Pourpoint	°C	<-6	<0	<6	-39	-24
MCRT	wt%	-	<0.3	<10	0	0
Net Heat of combustion	MJ/kg				41.6	42.0
Oxygen	wt%				< 0.5	<0.5
Ignition Temperature	°C				245	230
Nitrogen	ppm				18.3	0.5
Sulfur content	ppm	<1,000	<1,000	<5,000	4.6	2.0
Water	ppm	-	3,000	< 3,000	< 30	<30
Chlorine	ppm				<1	<1
DCN/ICN	-	40	35	860 (CCAI)	34.8	49.9
HFRR lubricity	µm	<520	<520		360	230
CFPP	°C	report	report		-41	>20
Oxidation stability (PetroOxy)	min	> 60	> 60	-	248	228

HPO Marine fuel – combustion testing

- Combustion testing **MARINE - A** in cooperation with Technical University Eindhoven.
- Experiments in a Combustion Research Unit (CRU).
- HPO produced from FPBO of different origin (softwood, miscanthus, lignin) and processing conditions.
- Lights (“naptha”) removed from HPO to achieve flashpoint of at least 60 °C
- Fuel blends with MGO and HVO.



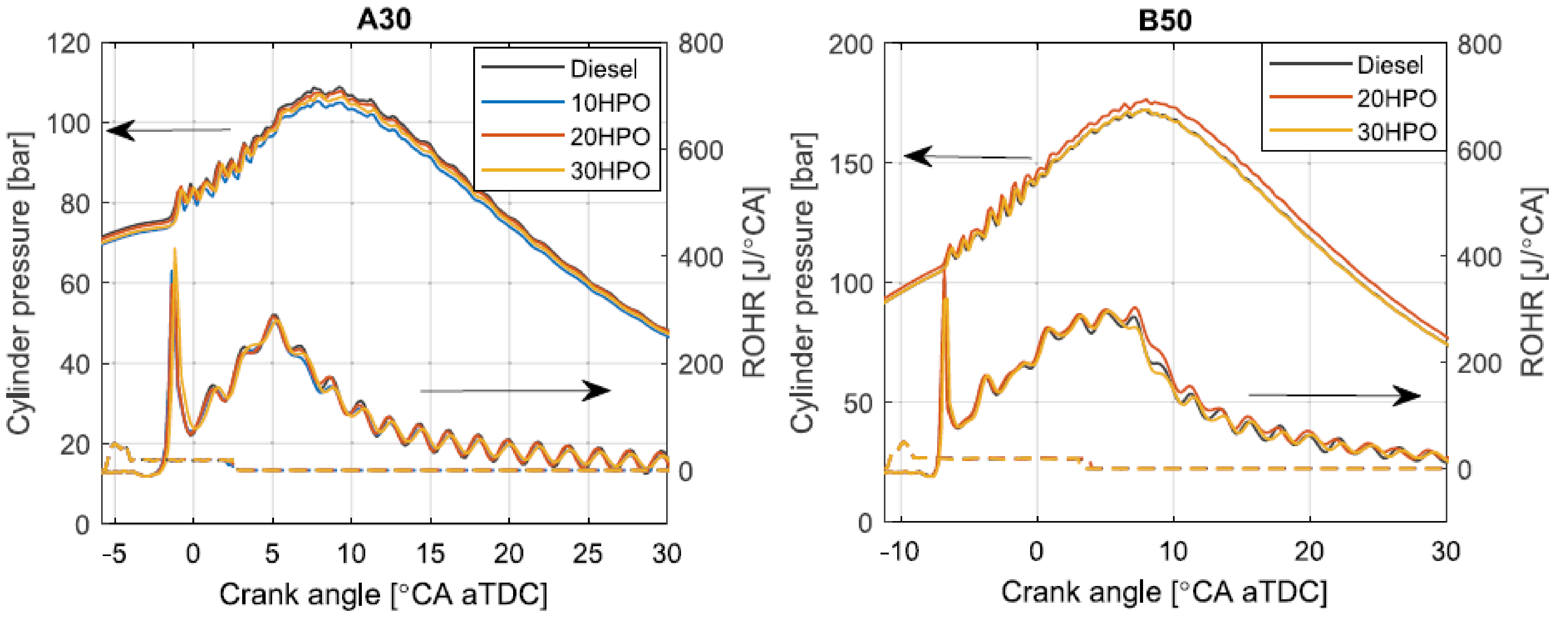
Ignition delay as function of chamber temperature for different fuels



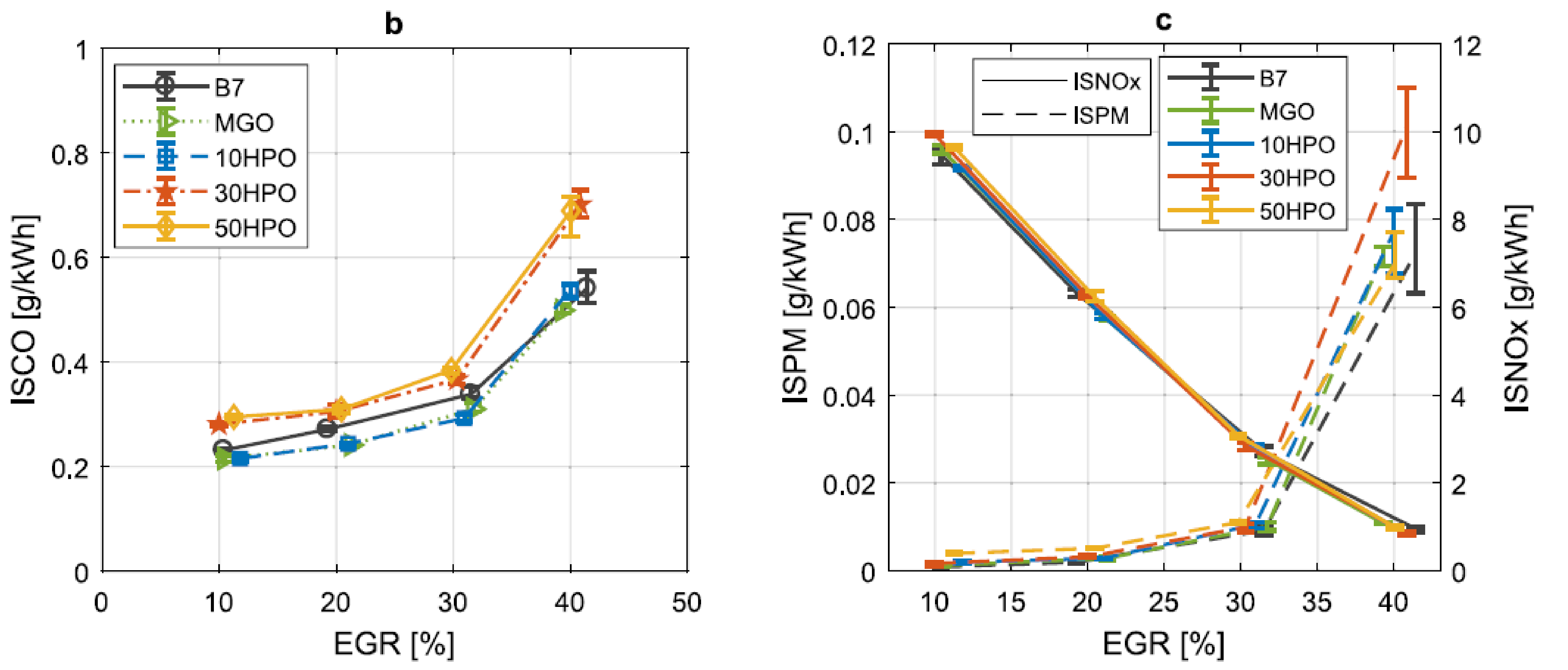
Chamber pressure and pressure rise for 75%HPO-HVO blend and EN590 diesel at T=535°C and T=565°C

HPO Marine fuel – engine testing

- 6-cylinder heavy duty engine (modified DAF MX-13), 1-cylinder active.
- Blends of up to 50% HPO Marine-A in MGO.
- HPO Marine-A derived from softwood.



Cylinder pressure as function of Crank Angle for MGO and MGO-HPO blends



CO, NOx and PM emissions as function of Exhaust Gas Recycle (EGR) for diesel, MGO and MGO-HPO blends.

Publications on "The use of Hydrotreated Pyrolysis Oil (HPO) in engines"

1. *Hydrotreated pyrolysis oil for marine application: fuel production and combustion performance*, Bert van de Beld, Hans Heeres, Bart Somers, Jinlin Han, Felipe Ferrari, PyNe 52, IEA Bioenergy Task 34, December 2022
2. *Ignition and combustion characteristics of hydrotreated pyrolysis oil in a combustion research unit*, Jinlin Han, Yu Wang, L.M.T. Somers, Bert van de Beld, Fuel 316 (2022), https://doi.org/10.1016/j.fuel.2022.123419
3. *Combustion and emission characteristics of hydrotreated pyrolysis oil on a heavy-duty engine*, Jinlin Han, L.M.T. Somers, Bert van de Beld, Fuel 351 (2023), https://doi.org/10.1016/j.fuel.2023.128888
4. *Experimental investigation performance and emission of hydrotreated pyrolysis oil in a heavy-duty engine with EGR*, Jinlin Han, L.M.T. Somers, Bert van de Beld, Fuel Processing Technology 255 (2024) 108061

Summary

- Fast Pyrolysis Bio-Oil (FPBO) can be upgraded to Hydrotreated Pyrolysis Oil (HPO).
- HPO is fractionated into Naptha, Sustainable Aviation Fuel (SAF) and Renewable Marine Diesel.

HPO-JET

- Physical-chemical properties of HPO-JET are close to the specs of Jet-A / Jet-A1 (ASTM D1655/D4054/D7566)
- HPO-JET is rich in cyclo-paraffins, and low in olefins & di-aromatics.
- Evaluation of combustion behaviour is on-going.

HPO - Marine diesel

- Different qualities marine fuel can be obtained
  A. HPO from lower severity upgrading and only removing the Naptha from HPO (“Marine-A”)
  B. Residue remaining after removal of Naptha and Jet fraction (“Marine-B”)
- Physical-chemical properties of HPO Marine diesel are close to specs of distillate or light residual marine fuels (ISO 8217:2024)
- Engine testing successful with HPO Marine-A in blends up to 50%; Adding some HVO is beneficial for combustion.

Acknowledgement

Renewell - Drop-in biofuels by catalytic hydrotreatment of pyrolysis oil for application in the marine sector.

TKI-BBEGR – Contract No. TBBE-118001

btg

GoodFuels
better world

TU/e

PureJet - Pyrolysis oil Upgrading for the production of Renewable Jetfuel.

TKI-Industry – contract No. TIND221002

btg

TU Delft
Delft University of Technology

SkyNRG

Thank you

EUBCE 2024
32nd European Biomass Conference & Exhibition

24-27 June | Conference & Exhibition
28 June | Technical Tours
Marseille

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