Diesel Engines with Microalgae Oil

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Microalgae oil is more or less equally sensitive to key engine parameters, compared with diesel fuel, and can be successfully adopted to the entire families of industrial diesel engines.

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1. Overview

A study conducted on the high-speed diesel engine (bore/stroke: 79.5/95.5 mm; 66 kW) running with microalgae oil (MAO100) and diesel fuel (D100) showed that, based on Wibe parameters (*m* and φ_z), the difference in numerical values of combustion characteristics was ~10% and, in turn, resulted in close energy efficiency indicators ( ) for both fuels and the possibility to enhance the NO_x-smoke opacity trade-off. A comparative analysis by mathematical modeling of energy and traction characteristics for the universal multi-purpose diesel engine CAT 3512B HB-SC (1200 kW, 1800 min^{-1}) confirmed the earlier assumption: at the regimes of external speed characteristics, the difference in P_{me} and η_i for MAO100 and D100 did not exceeded 0.7–2.0% and 2–4%, respectively. With the refinement and development of the interim concept, the model led to the prognostic evaluation of the suitability of MAO100 as fuel for the FPT Industrial Cursor 13 engine (353 kW, 6-cylinders, common-rail) family. For the selected value of the indicated efficiency   = 0.48–0.49, two different combinations of φ_z and *m* parameters (φ_z = 60–70 degCA, *m* = 0.5 and φ_z = 60 degCA, *m* = 1) may be practically realized to achieve the desirable level of maximum combustion pressure P_{max} = 130–150 bar (at α~2.0). When switching from diesel to MAO100, it is expected that the   will drop by 2–3%, however, an existing reserve in P_{max} that comprises 5–7% will open up room for further optimization of energy efficiency and emission indicators.

2. Diesel Engine Technology

Today, the world is challenged with the twin crises of fossil fuel reduction and environmental degradation. Unselective extraction and excessive consumption of fossil fuels have led to a decrease in underground-based carbon capitals. The hunt for alternative energy, which assures a positive correlation with sustainable growth, energy conservation and management, efficiency, and ecological protection, has become extremely marked over the last two decades.

The entire transport sector, including industries providing transportation, agree on the need to decarbonize traffic before 2050–2060 for the most developed and 2060–2080 for less developed economies [1][2]. Usually, this roadmap is primarily associated with the wider deployment of electric transport. It is likely that different energy vectors (CNG, LPG, synfuels, vegetable oils and biodiesel, GTL, H_2, electricity—see Table 1) will play a role in transport decarbonization [3]. If properly allocated to hard-to-decarbonized modes of transport, synfuels and sustainable biofuels, coupled with the direct electricity consumption through either electrified railways or battery electric vehicles, will all be important in the process of reducing 'carbon intensity' in transport [3]. The European Union member countries alone consume approximately a fourth of the petroleum exploited globally per year. Global consumption of petroleum products has been growing as a result of the rapid development of Asian economies (China, India) as well. EU authorities have recently started referring to new pollution and climate change control measures more frequently. There is a unanimous consensus within the community on securing long-term clean energy supplies for Europe, in addition to the reduction of greenhouse gas (GHG) emissions from the transport and energy sectors. Lower environmental pollution and higher economic efficiency are probably the biggest advantages of fuel alternatives to gasoline and diesel. However, several studies [4][5] provide readers with the counter argument, that a massive replacement of combustion engine-powered vehicles by battery electric vehicles alone cannot deliver greenhouse gas reductions consistent with climate stabilization and, in the future, may lead to the depletion of key mineral deposits, such as magnesium and lithium. The producers of the high-power industrial diesel engines of low- and average-speeds see fuel flexibility and robustness (VLSFO/MGO, 20% H_2 in NG, biofuels, MeOH, NH3, H_2 as future alternatives) as the key advantage and offer a wide range of sector-specific scenarios, outlining the potential benefits of a particular fuel choice.

Table 1. Alternative fuels currently being heavily studied for transport applications.

Types of Fuel	Description
Oils and biodiesels (including microalgae oil and biodiesel), BTL (biomass-to-liquid), and alcohol fuel [6][7][8][9][10]	**Because they are produced in plants that chemically 'fix' or capture carbon dioxide, these types of fuel are characterized for their low environmental pollution. Nonetheless, the production of such fuels requires large amounts of energy if compared with gasoline or diesel fuel.**
Gas-to-liquid (GTL) [11][12][13]	**Used as a substitute for diesel fuel, as GTL leads to a significant reduction in air pollution from internal combustion engines.**
Synthetic fuels (or synfuels) [14][15]	**Production of synthetic diesel fuels obtained from biomass, household waste, and/or natural gas has begun approx. 20 years ago. Synfuels are not considered as alternative fuels since they do not require any modifications in the fueling infrastructure or engine design. However, synfuels expand the raw materials base as well as enhance biodiversity and restore the natural ecological balance due to their easy quality assurance during the production process.**
Compressed natural gas (CNG) and liquefied natural gas (LNG) [16]	**CNG and LNG both are highly functional and efficient type of fuel gas. Theoretically, natural gas resources are vast, if not taking into account the global geopolitics. If we take into consideration the geopolitical situation in the world, specialists believe they may be depleted by 2060. Hence, natural gas is playing a large role in near-future energy prediction. The advantage of CNG/LNG compared with other types of alternative fuel is lower CO_2 emission and a higher heating value (48.7 MJ/kg) in comparison to diesel fuel (42.6 MJ/kg). Currently, nearly all European automobile manufacturers offer natural gas-powered vehicles to the market. Most of them can run both on gasoline and on natural gas, however, bi-fuel engines lead to higher environmental pollution if compared with those running only on natural gas.**
Liquefied petroleum gas (LPG) [17]	**LPG (mainly propane and butane) is prepared by refining raw natural gas or crude oil and is a co-product of the refining process. This type of fuel is highly explosive. Moreover, LPG characteristics are different from those of the diesel fuel, which means that engines designed for both types of fuel are inefficient.**
Hydrogen (H_2) [18]	**Hydrogen in gaseous or liquid form may be used in conventional internal combustion engines. This type of fuel carries three times more energy than gasoline; however, density of the former is significantly lower even when compressed. Moreover, a significant amount of electrical energy is required for H_2 generation.**

There is a widespread consensus that diesel engine technology has not reached its full maturity and potential yet, in terms of efficiency or lower carbon impact [1]. This is an advanced technology through which synthetic, zero-emission fuels can be produced using only renewable energy and CO_2 [1]. Fuels such as H_2, GTL, CNG, 3rd generation microalgae fuels, and synthetic hydrocarbons that are made using energy from renewables or other low-carbon energy sources could play a role in multiple hard-to-decarbonize sub-sectors of global transportation [19]. There is also another key, future-oriented reason that should motivate legislators and OEMs to keep diesel engines in the game: power-to-fuel or power-to-x [1][20]. Synthetic fuels made from carbon dioxide captured from the air or 3rd generation microalgae fuels made from CO_2 captured from industrial power plants can be successfully used as transportation fuels in conventional engines.

Gaps in the literature, which we are trying to fill. The goal of the overall transport sector is to largely decarbonize and move from 7.7 metric gigatons of emissions per year to 3-2 metric gigatons by mid-century (2050), while ensuring climate resilience. Based on IEA data, predicted global demand for fuel and energy by the transport sector will increase by 140%, 75%, and 70% in aviation, freight transport, and passenger cars, respectively, between 2000 and 2050 [20]. As for the EU transport sector, the agreement was obtained in 2018 that a 14% RES target by 2030, including the gradual phase out of crop-based biofuels from 7% in 2020 to 3.8% in 2030 and a 3.5% share of advanced biofuels of 2nd and 3rd generation. As described previously, all kinds of alternative fuels being heavily studied for transport applications today will all be essential in the process of reducing 'carbon intensity' in transport. The main advantage of the 3rd generation microalgae oil-powered heavy-duty engine over other alternative fuels is that such a vehicle can be relatively called 'CO_2 neutral'—a feature which is characteristic to the very limited variety of fuels of the future (synfuels, power-to-x, etc.) [8]. Notwithstanding the large amount of research studies conducted so far, the majority of the dedicated works are limited to an assessment of diesel engines of a particular modification and presentation of the insights and recommendations obtained for the engine-specific scenario [6][7][8]. This situation usually leads to the disparity between the total quantity of recorded knowledge and the limited capacity of researchers, government bodies, and legislators to assimilate it as well as take action [6][7][8]. This was the main reason behind the prognostic assessment of the industrial diesel engine family for energy efficiency and CO_2 levels and to take a broader look at pure microalgae oil, a potentially carbon-free resource, as a candidate for future transportation energy mix. This study is a part of larger scale investigation conducted by co-authors in the field of transport decarbonization.

3. Conclusions

This entry raises a concern regarding the mass usage of fossil fuels mined from ancient deposits and consumed by industrial engines which are extensively used in various industries and sectors of the economy by offering to replace conventional fuel as a constituting part of the final energy mix with a novel type of biofuel produced from the less investigated microalgae specie *P. moriformis*. The following conclusions can be drawn as a result of the research:

- The interval of −2… 0 degCA was found to be the best setting of an engine for smoke and NO_x stabilization and reduction, nevertheless D100 or MAO100 were used. That leaves many opportunities for the wider deployment of their binary blends of various ratios to be consumed in diesel engines. Moreover, the pilot study showed that the use of microalgae oil in passenger car engine positively affected the indicated thermal efficiency (η_i) of the prime mover, finding it very similar to that of diesel fuel: 0.355 and 0.350 (P_{me} = 0.8 MPa), 0.350 and 0.345 (P_{me} = 0.6 MPa), 0.325 and 0.320 (P_{me} = 0.4 MPa).

- Following accuracy of the 1-D predictive engine model was obtained for various parameters: p_{me}: 0–4.3%, p_K: 2.5–4.5%, α: 5.1–10.0%, λ: 0–3.9%, η_e: 0.3–3.4% and g_{cycl}: 0–1.7%, T_K: 0.8–1.7%, p_c: 0.6–1.7%, p_{max}: 1.6–3.9%, T_g: 1.9–3.2%.

- For the CAT 3512B HB-SC engine running with microalgae oil, we proposed a boundary condition for the injection modelling settings ($T_g \leq 973$ K, φ_{inj} = 2 degCA BTDC) that led to improvement of the overall traction characteristics: the difference in η_i was almost eliminated and comprised only 0.7–2.0% without any compromise in exceeding the threshold value of 973 K for exhaust gas temperature.

- An extensive simulation of the FPT family engine, type Cursor 13 was performed by taking into account different strategies of a combustion process duration and its dynamics through the adjustment of m and φ_z parameters within the broad range of variation: m = 0–1.5, φ_z = 50–80 degCA. The obtained results revealed that, if considering the smallest changes in the indicated thermal efficiency values as an outcome of the best compatibility of m and φ_z parameters, this indicator can be characterized by a relatively short period of heat release (50–60 degCA) and moderate dynamics (m = 0–0.5).

- The zones of rational combination of m and φ_z were identified for each operational parameter of the engine to facilitate the smooth transition to microalgae oil. It was found that the differences in carbon dioxide emissions within the zone of rational combination of m and φ_z parameters did not exceed 4–5% if compared with D100.

- The study found that microalgae oil is more or less equally sensitive to key engine parameters, compared with diesel fuel, and can be successfully adopted to the entire families of industrial diesel engines.

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