Fuel Dependent Heat Release Differences between Euro Diesel Fuel and RME in a HSDI Diesel Engine

U. Horn[1], R. Egnell[1] and Ö. Andersson[2]

[1] Lund Institute of Technology, SWEDEN
[2] Volvo Car Corporation, SWEDEN

In the degree that costs and demand of crude oil rise, diminish the economical disadvantages for alternative Diesel fuels, resulting in a variety of feasible substitutes. Diesel fuel substitutes have deviating exhaust emissions from conventional fuel. The methyl ester of rapeseed oil (known as RME/Biodiesel) is receiving increasing attention as an alternative fuel for Diesel engines. RME is a non-toxic, biodegradable, and renewable fuel with the potential to reduce engine exhaust emissions [1]. The main disadvantage for RME is its vaporisation and self ignition characteristics at low load conditions.

Engine experiments were carried out at 4 bar IMEP with Euro Diesel fuel (EDF) as reference and RME. During these engine experiments EGR and injection pressure were varied. As a result, differences in exhaust emissions due to EGR, injection pressure and fuel type were observed.

The objective of this work was to find answers for fuel dependent differences in indicated load and exhaust gas emissions. As combustion and emission formation of RME has not been fundamentally explained yet [2], a detailed analysis approach based on explanation models for fuel characteristics was chosen to explain the observed differences.

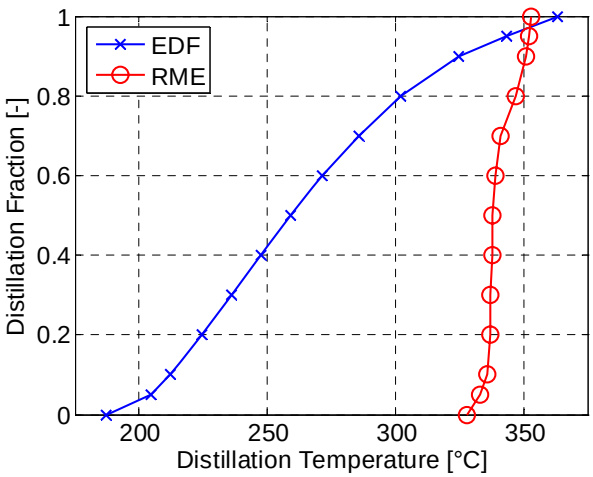
FUEL CHARACTERISTICS

SAUTER MEAN DIAMETER

Spray vaporisation properties for RME deviate considerably from EDF. This is due to increased fuel viscosity and surface tension which entail larger average droplet size. A measure for the average droplet size is the Sauter Mean Diameter (SMD): The strongest parameters influencing SMD are the velocity difference between fuel and cylinder charge (u_g), the fuel viscosity and fuel surface tension. As u_g is highly dependent on injection pressure, it is presumed that SMD is considerably influenced by increasing injection pressure.

DISTILLATION CURVE

Fuel characteristics are described by the shape of the distillation curve [3]: The cetane number of the fuel fraction vaporising during the start of the distillation curve has an influence on exhaust emissions: A low initial fuel cetane number (ICN) increases ignition delay. Hence, both PM and NOx-emissions are lower with ICN improvers even though the overall fuel cetane number is virtually unaffected.



A flat distillation curve is advantageous due to a lower fuel evaporation rate over the

whole distillation temperature interval. It has been reported that thermal engine efficiency increases due to a better controlled vaporized fuel supply during the whole combustion process [3].

Even though the CN for RME is slightly higher than for EDF, combustion properties are reported to be poor at low load conditions [3,4,5]. This is due to the composition of RME: RME consists of a few types of acid ethyl esters with similar properties whereas EDF consists of 200 different hydrocarbon types with varying properties. Hence, RME can be considered as a virtually pure substance with a very high distillation curve gradient (cf. Figure above – Distillation Temperature): Especially under low load conditions, fuels with a strong distillation temperature gradient cause HC-, CO- and PM-emissions. HC- emissions are produced by incomplete combustion due to poorly controlled fuel vaporisation as a result of a short distillation temperature interval.

The initially vaporised fuel fraction has a major influence on ignition delay. Thus, a high boiling point increases ignition delay as more time is needed to vaporise the initial fuel fraction.

For the differences in fuel characteristics between EDF, RME, the following is summarised:

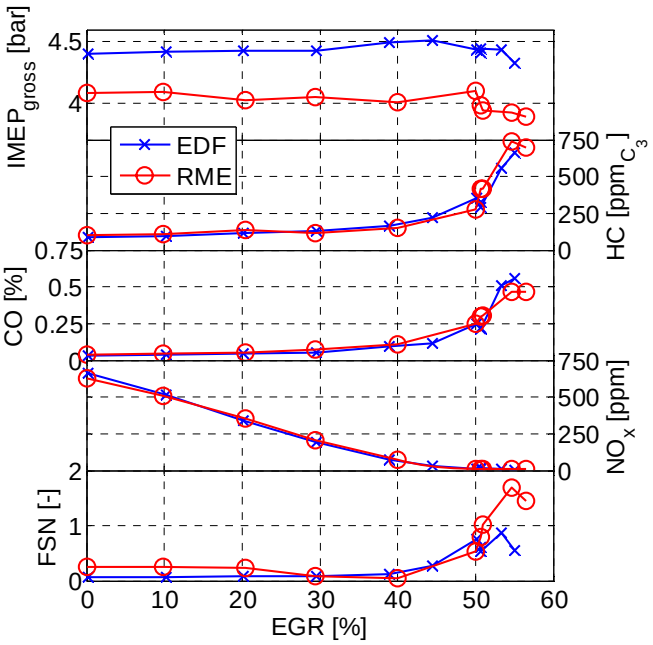
- EDF (certification fuel) was chosen as the reference fuel. It contains ignition delay improvers with low ICN and oxidation characteristics are improved by a low volatile fuel fraction with high FCN.

- For RME, fuel properties as viscosity, heat capacity, boiling point, distillation curve, volatility and chemical structure are different from EDF. This means that formation and growth of particulates during combustion as well as oxidation characteristics differ considerably.

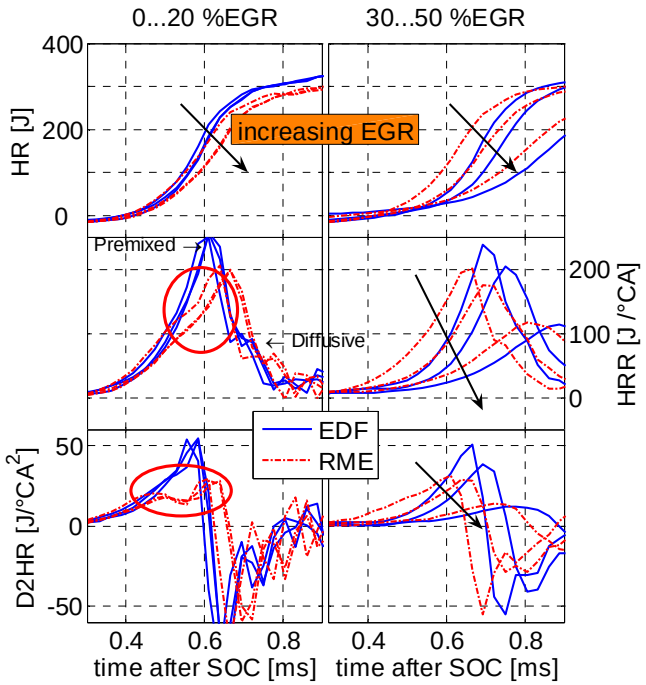
RESULTS

Influence of EGR and Fuel Type

Emissions changed during variation of EGR under constant fuelling rate. Fuelling rate was adjusted for differences in density and heating value in order to inject the same amount energy for both fuels. Fuel specific differences in indicated mean effective pressure of the combustion phase ($IMEP_{gross}$) and exhaust emissions were observed. Exhaust emissions converged for both fuel types with increasing EGR level.



These observed differences are explained by comparison of the rate of heat reease (HRR) between 0 and 50% EGR: As shown in the figure below both, premixed and diffusive HRR is



lower for the RME case. At low load conditions, RME is considered as a poorly ignitable diesel fuel [3 pg. 125ff] which is due to a high distillation middle temperature (T50): If it is assumed that the overall liquid fuel spray has to be heated until T50 to become vaporised, and if it is moreover assumed that heat capacities for both fuel types are alike, the heat needed for warming up the liquid spray phase to vaporisation conditions is higher. Due to the high distillation temperature gradient, more time is needed for vaporisation of the initial fuel fraction, which increases ignition delay somewhat.

Due to RME's mono component like short distillation temperature interval a large fuel spray fraction vaporises concurrently within a small temperature and spatial interval if enough ambient heat is available. Together with a larger average droplet size due to higher fuel viscosity increase these fuel characteristics the affinity of RME to form a higher amount of fuel rich reaction zones at start of combustion. This is reflected in a lower overall HR due to poor premixed and diffusive combustion (see figure above).

Both, overall and premixed HR is delayed for the RME case between 0...20% EGR which is in accordance with a decrease in maximum HRR. If EGR level is increased above 30%, the point of maximum HR is more delayed for the EDF case which is in contrast to the 0…20% EGR cases. This behaviour is related to the ignition delay which increases with EGR level. The time delay between SOC and maximum HRR (HRR_{max} – see figure above) is a function of mixture quality; hence, the ignition delay for the RME case at EGR levels above 30% is an indicator for improved mixture generation.

Ignition delay of RME was similar to EDF. For EDF, the ICN is lower than the overall CN to increase ignition delay. For RME against that, the ICN is equal to the overall CN. The ICN is considered to have the strongest influence on ignition delay. Hence, the similar ignition delay between EDF and RME is related to a longer evaporation process for the RME-case; more time is needed to form an ignitable fuel-air mixture.

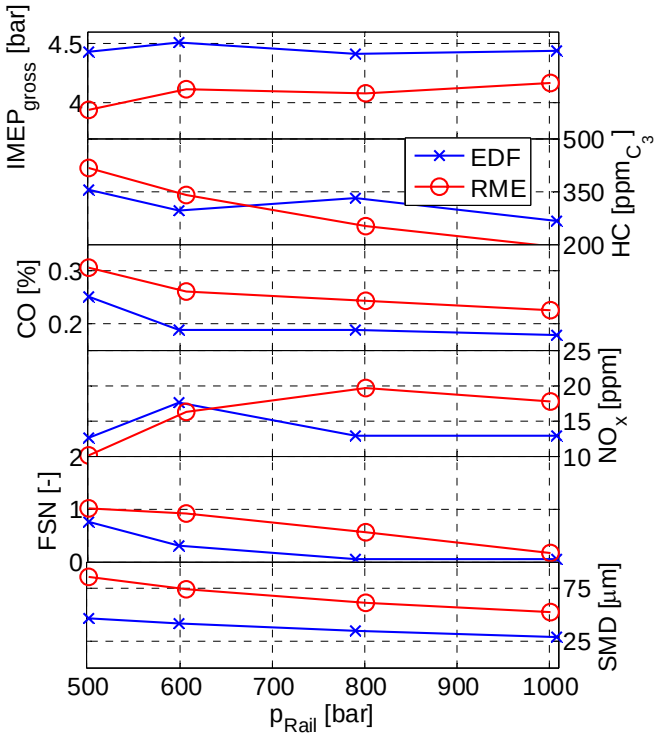
For the influence of EGR on different fuel types, the following is concluded: For the RME case, overall HR as well as the maximum HRR is lower than for EDF. For EGR levels above 30%, combustion phasing was slightly earlier than for the EDF-case which was in contrary to low EGR levels. This is an indication for an improvement in mixture generation for the RME case with higher EGR levels due to increased ignition delay.

<u>Influence of Rail Pressure</u>

The variation of rail pressure led to a further indication for the assumption of locally fuel rich combustion of RME as the source for PM. Observed differences in HR for EDF and RME were considerable:

A decrease in ignition delay and combustion duration was observed, while HR_{max} and HRR_{max} increased concurrently with higher injection pressure. Increased HR_{max} is an indication for improved mixture generation. This indication is emphasised by calculation of average droplet size. In the following picture is depicted, that SMD and exhaust emissions are considerably influenced by injection pressure:

Injection velocity is the strongest factor influencing SMD. Increasing injection pressure increases relative velocity between injected fuel und cylinder charge. Hence, average droplet size is reduced which improves vaporisation characteristics for all fuels. RME has a larger SMD due to higher fuel viscosity and benefits stronger from increasing injection pressure. This benefit is reflected in decreasing emissions and increasing IMEP. For the influence of increasing injection pressure on HR, the following is summarised:



- Average droplet size decreases with injection pressure, which improves fuel spray evaporation characteristics.

- Improved fuel mixture generation is reflected in improved HR_{max}, shorter ignition delay and shorter combustion duration.

- The fuel type RME benefits stronger from increased injection pressure than EDF. This is related to a stronger reduction in SMD compared with EDF.

CONCLUSIONS

Measurement results from a HSDI Diesel engine were studied by detailed heat release analysis. For both fuel types, increasing EGR levels increase ignition delay, which improves mixture generation and premixed combustion. Increasing EGR level entails a longer premixed combustion duration, which lowers maximum HRR. In this way the amount of fuel rich, locally hot zones is minimised. Hence, PM emissions originating from fuel rich combustion were improved.

RME showed different combustion characteristics from EDF at low load conditions which depend on the following factors:

- Injection duration was longer for the RME case due to lower fuel energy content. This resulted into less available time for fuel mixture generation; a larger fuel fraction was injected close to or after SOC, which influenced HRR at low EGR conditions.

- For RME, the high ICN resulted into early ignition of fuel rich zones entailing suboptimal premixed HR which was indicated by lower maximum HR.

- Due to higher fuel viscosity, SMD is increased for RME. Increased average droplet size increases the affinity to form locally fuel rich zones. Fuel dependent SMD differences are compensated by increased injection pressure.

- RME combustion characteristics can be considered as poor at low load conditions. Due to a high distillation middle temperature, short distillation temperature interval and increased SMD, fuel vaporisation is delayed. Premixed HR is unsteady due to concurrent fuel spray evaporation and premixed combustion.

- The ratio of diffusive and premixed HR is lower for RME than for the reference fuel. This is related to the lack fuel components that improve FCN. The lower diffusive HR entails poor emission oxidation characteristics.

If alternative diesel fuels with varying properties shall be included in future emission legislations, technical possibilities exist to meet these legislations: Today's Diesel engines are equipped with advanced combustion control devices like EGR, Common Rail and Turbo Charging. In addition, fuel and/or cylinder pressure sensors open possibilities for a multi fuel production engine. If engine control strategy is adapted to a specific fuel type during operation, emission demands can be met for a variety of fuels.

REFERENCES

1. Hopp, M.: "Untersuchung des Einspritzverhaltens und des thermischen Motorprozesses bei Verwendung von Rapsöl und Rapsmethylester in einem Common-Rail-Dieselmotor", Dissertation Universität Rostock 2005

2. R. L. McCormick, C. J. Tennant, R. R. Hayes, S. Black, J. Ireland, T. McDaniel, A. Williams, M. Frailey: "Regulated Emissions from Biodiesel Tested in Heavy-Duty Engines Meeting 2004 Emission Standards", SAE 2005-01-2200

3. Garbe, T.: "Senkung der Emissionen eines PKW mit direkteinspritzenden Dieselmotor durch Verwendung von Kraftstoffen mit abgestimmtem Siede- und Zündverhalten", Dissertation Universität Hannover 2002

4. Chang, D., Van Gerpen, J.: "Determination of Particulate and Unburned Hydrocarbon Emissions from Diesel Engines Fueled with Biodiesel", SAE 982527

5. Mayer, A.C.R., Czerwinski, J., Wyser, M.: "Impact of RME/Diesel Blends on Particle Formation, Particle Filtration and PAH Emissions" SAE 2005-01-1728