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Optimization of the DPF-Regeneration Strategy for the Use of Vegetable Oil in a Multi-Fuel-Engine Concept

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Abstract

The move away from fossil fuels and the diversification of the primary energy sources used are imperative both in terms of mitigating global warming and ensuring the political independence of the Western world. For the industries of agriculture and forestry, it is possible to secure the basic energy supply through their own yield. The use of vegetable oil is a possibility to satisfy the energy requirements for agricultural machines both autonomously and sustainably. Up to now, rapeseed has been the most important plant for oil production in Western Europe. In the EU, rapeseed oil is currently credited with up to 60% fossil CO_2 savings compared to conventional diesel fuel. As a result, since 2018, rapeseed oil is no longer considered as biofuel in the EU. However, if cultivation and processing are completely based on renewable energy sources, up to 90% of fossil CO_2 emissions can be saved in the future. This also applies to rapeseed oil, which is a by-product of animal feed production. In addition, pure rapeseed oil is chemically unchanged and thus biodegradable, which makes it particularly attractive for use in environmentally sensitive areas.

To increase the attractiveness of rapeseed oil as a fuel for the agricultural industry, a multi-fuel concept for the flexible use of rapeseed oil, diesel fuel and any mixtures of these two fuels would be beneficial, as it minimizes economic risks due to price fluctuations, availability, and taxation. For implementing such a concept, technical adjustments to the propulsion system are necessary. In existing vegetable oil vehicles, cost-intensive additional components are required for diesel particulate filter regeneration. Conventional regeneration via post-injected fuel (which does not participate in combustion) leads to dilution of the engine oil with vegetable oil.

This study elaborates the possibilities of DPF regeneration in vegetable oil operation by internal engine measures without the need for post-injection. This includes strategies for generating exhaust gas temperatures in high-idle operation which are suitable for regeneration. For this purpose, strategies combining throttling and retarded combustion are used. The measures were successfully tested with respect to their effectiveness for DPF regeneration. It could also be proved that no increased engine oil dilution occurs as a result of the regeneration procedure.

For a prospective series application, however, regeneration should also be possible in transient engine operation. For this purpose, the measures developed for high-idle regeneration have been transferred to partial load points to gain insight into their applicability for transient engine operation. In addition, the effect of external EGR on regeneration has been considered. As the previous investigations of high-idle regeneration showed that regeneration is most critical when pure rapeseed oil is used, the studies of regeneration in part-load operation were limited to pure rapeseed oil. The systematic parameter variations carried out during the studies helped to improve the understanding of the system and the mechanisms of regeneration. The results of the investigation show that the exhaust gas temperature can be increased significantly by the measures studied. However, achieving the exhaust temperature required for DPF regeneration remains a challenge for certain operating points.

1. Introduction

To minimize the anthropogenic influence on the greenhouse effect, CO_2 emissions from fossil fuels must be stopped in the long term. Increasing global political and social uncertainty shows, especially in Western Europe, that dependence on fossil fuels is not only questionable in terms of climate policy, but also harbors economic and foreign policy risks. To meet climate targets and secure political sovereignty, it is necessary to diversify primary energy sources and use a variety of energy producers.

In the passenger car sector, there is already a clear trend towards battery electric drives, which, do not offer a universal solution for vehicle requirements in the non-road sector due to the currently still limited possibilities. For work machines, it is therefore necessary to consider other renewable energy sources [1].

The total energy demand in the German transport sector was around 635 TWh in 2017. Of this, approximately 390 TWh is diesel fuel according to DIN EN590. This includes 7 % biodiesel, which accounts for 63.3 % of renewable energies in German transport. Figure 1 illustrates the shares of renewable energy sources in the transport sector in Germany from the year 2021 [2].

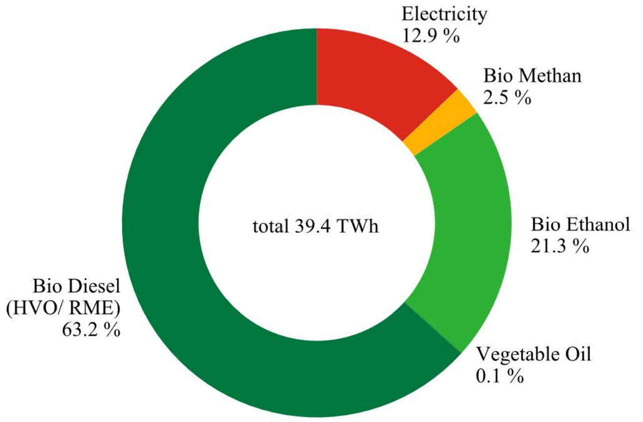


Figure 1: Shares of renewable energy sources of germane transport sector (data taken from [3])

Based on a share of 39.4 TWh of renewable energy sources, approx. 25 TWh are covered by bio diesel. Due to an increasing degree of electrification of drives in the transport sector, it is foreseeable that a share of renewable energy sources will be available for other or specific applications. As an example, a complete or extensive electrification of mobile machinery in the agricultural sector is not foreseeable. The share of biodiesel available today (approx. 25 TWh) would be sufficient to fully cover the consumption of diesel fuel in agriculture (approx. 20.5 TWh). Since bio diesel is produced from vegetable oil, it is also possible to cover the agricultural energy demand with pure vegetable oil. This would make it conceivable to secure the basic energy supply through own yields [2,4].

Since 2018, EU legislation has stipulated that biofuel must save at least 60 % CO_2 compared to fossil diesel fuel. Figure 2 shows the current eligible CO_2 savings of various sustainable fuels compared to fossil diesel fuel [5].

By assuming that fossil CO2 emissions are caused by cultivation, processing and transport, vegetable oils thus no longer meet the EU requirements for biofuels. Considering that cultivation and processing are carried out in the long-term using renewable energies, up to 90 % of fossil CO_2 emissions can be saved. This is already the case for oil, which is a by-product of animal feed production. In addition, pure vegetable oils are chemically unchanged and thus biodegradable, which also speaks in favor of their use in environmentally sensitive areas such as agriculture [5].

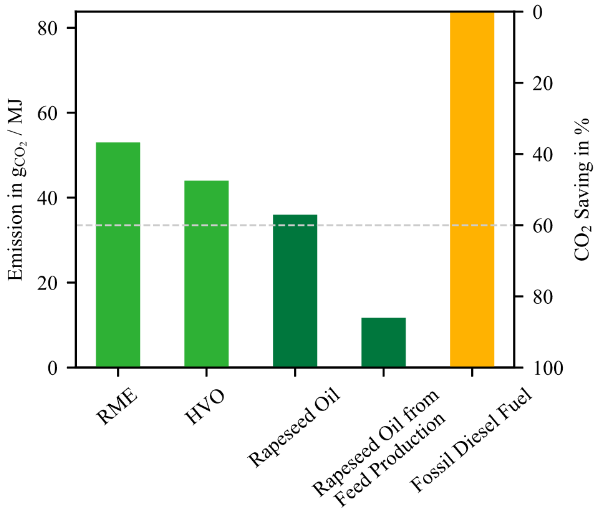


Figure 2: Savings of fossil CO_2 emission from several biofuels in comparison to fossil diesel fuel (data taken from [5])

This means that vegetable oil can be used to provide the primary sector with a sovereign supply of energy, while at the same time meeting the requirements for energy density of the drive system, environmental protection, and climate protection. To be able to use this technology efficiently, it is necessary to continue research into vegetable oil combustion processes and motor operations when using vegetable oil.

2. DPF Regeneration

The diesel particulate filter (DPF) is an integral part of the exhaust gas aftertreatment system in modern diesel engines. The task of the DPF is to filter out solid components (particulates) from the exhaust gas. As the amount of filtrate increases, the flow resistance grows, resulting in an increase in exhaust backpressure. This results in an increase in the internal work of the engine, which in turn leads to a reduction in effective efficiency. Regular regeneration of the diesel particulate filter is therefore essential. Regeneration is possible in two different ways [6,7].

2.1 Active DPF Regeneration

For active regeneration, the filter temperature must be raised to the ignition temperature of the soot (approx. 530 °C) by means of engine modifications. Another prerequisite is enough residual oxygen in the exhaust gas (>5 %) for rapid regeneration. The soot burns to CO_2 with the release of heat by means of oxygen. The heat generated can cause temperatures of over 1000 °C in the filter, which can lead to damage to the substrate (cracking, melting or reduced permeability). To avoid this, it is important not to exceed the specific loading limit of the filter (5 - 10 g/l depending on the filter material) and to initiate regeneration at an early stage if necessary [6,7].

Since the exhaust gas temperature does not exceed the ignition temperature in all diesel engines and only in a few map ranges, regeneration must often be actively initiated. For this purpose, fuel is introduced into the engine's exhaust stroke, which evaporates but does not participate in combustion. These unburned hydrocarbons are then converted in an exothermic reaction at the diesel oxidation catalyst, which results in an increase in exhaust gas temperature [6,7].

2.2 *Passive DPF Regeneration*

Passive regeneration already takes place at temperatures of 250 - 300 °C. In this process, the soot is continuously oxidized by means of NO_2 and/or oxygen (O_2), for which complete oxidation requires the presence of approx. eight times the mass of NO_2 compared to soot. At sufficient temperature and mass ratio, on average as much soot is oxidized as new soot is deposited and an equilibrium loading (balance point) is reached. Below a temperature of 400 °C, the oxidation of soot by means of NO_2 predominates. Only above 400 - 450 °C does continuous oxidation by means of oxygen gain in importance [6,7].

2.3 *Active DPF Regeneration with vegetable oil*

In active DPF regeneration, fuel is injected into the combustion chamber. To evaporate this injected fuel, a corresponding temperature level and heat is required in the combustion chamber. This gives rise to the problem of active regeneration with vegetable oil. Figure 3 shows the boiling curves of fossil diesel fuel, RME and pure rapeseed oil. As can be seen in the figure, diesel fuel already begins to boil between 150 °C and 200 °C. The boiling point of rapeseed oil is between 150 °C and 200 °C. By comparison, the boiling point of rapeseed oil does not start until 300 °C [8,9].

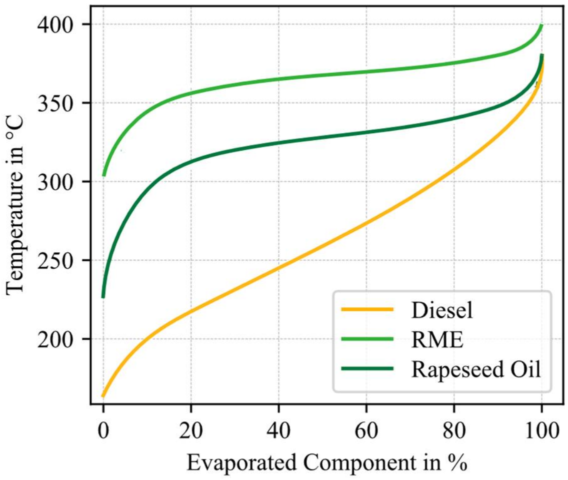


Figure 3: Evaporation curves of diesel, RME and rapeseed oil (data taken from [9][10][11])

At this temperature, 75 % of the diesel components have already evaporated. Diesel reaches complete vaporization at a temperature of around 350 °C. RME only begins to boil here [8,9].

Even above this temperature, the cylinder walls are covered with a thin oil film, which remains stable even during combustion. Unvaporized or incompletely vaporized rapeseed oil or RME is deposited on this and enters the engine oil via the upward movement of the piston and the oil scraper rings. If post-injected diesel fuel reaches the engine oil, most of the fuel components can evaporate again due to the low boiling temperature and outgas from the oil. This is not possible with rapeseed oil and RME, so the fuel remains in the oil. As a result, the oil pan may be overfilled and/or the lubricity of the diluted engine oil reduced. However, if the fuel remains in the engine oil for a longer period, sludging occurs, in which case the viscosity rises sharply again. The reason for this is the double bonds of the fatty acid chains, which cause auto-oxidation of the fuel. This process is called aging of the engine oil. If the sludged oil is pumped through the oil ducts, the ducts and the oil filter can become clogged, resulting in fatal engine damage [7,10,13,14,15].

To carry out this process in previous vegetable oil-compatible vehicles, additional components were used. It is possible, for example, to introduce hydrocarbons directly into the exhaust gas by means of an HC doser, or to burn them directly by means of a catalytic burner, thus adding heat to the exhaust gas. However, these components involve additional costs and installation space, which reduces the attractiveness of the vehicles. Further information can be found elsewhere [13,16,17].

3. Methods for increasing exhaust gas temperature

To reduce pollutant emissions, it is necessary to bring the exhaust gas aftertreatment system up to operating temperature as quickly as possible, and to ensure that it does not fall below this temperature. Various measures are available for this purpose, which have already been investigated and implemented on production diesel engines. The most important methods for increasing the exhaust gas temperature are:

- post-injection: In this process fuel is injected into the combustion chamber during the ejection stroke. The fuel is vaporized but does not itself take part in combustion. The unburned hydrocarbons are then converted at the diesel oxidation catalyst in an exothermic reaction. The heat released in this way generates a temperature increase in the subsequent exhaust gas aftertreatment. For the conversion of the hydrocarbons, however, the DOC must already be at operating temperature [6].
- throttling: throttling the fresh air mass flow or the exhaust gas mass flow increases the gas exchange work of the engine and at the same time reduces the effective efficiency. With reduction of the thermal mass of the exhaust gas flow, the exhaust gas temperature also increases [7].
- hot EGR: By introducing hot combustion gases into the combustion chamber by means of internal exhaust gas recirculation, it is possible to raise the process temperature and thus also increase the exhaust gas temperature at low load points. The prerequisite for this is a so-called second event, in which the exhaust valve is opened a further time during the intake process. This can be achieved, for example, by means of a variable valve train [18,19].
- cylinder deactivation: by deactivating individual cylinders, also known as load point shifting, both combustion temperature and exhaust gas temperature are increased and the effective efficiency at low engine load increases. A variable valve train or deactivatable camshafts are required for implementation [20,21].
- early exhaust opening: By adjusting the exhaust camshaft, it is possible to open the exhaust valve at higher cylinder pressure and gas temperature. Since the gas has less time to convert heat into mechanical work, more heat is transferred

to the exhaust gas. As a result, the exhaust gas temperature rises [18,22].

The measures described above for increasing exhaust gas temperature and their effectiveness have already been investigated in numerous studies. Attention has also been paid to fuel consumption [20,22].

It has been shown that cylinder deactivation is the most effective measure in terms of fuel consumption since fuel consumption can still be improved in this way despite the increase in temperature. However, the technological effort required for feasibility is enormous, both in terms of engine components and application effort. In [23] various alternatives to cylinder deactivation are investigated, in which part of the cylinders is bypassed without the intake and/or exhaust valves being completely deactivated. For this purpose, the opening duration is significantly increased for the valves of the unfired cylinders, or the valve spread is increased to open the valves around bottom dead centre. Investigation of these strategies revealed similar potentials in terms of temperature increase and fuel consumption as with complete cylinder deactivation. However, a high degree of variability in the valve train is also required, which means additional technological expense.

4. Previous Investigations

The usage of pure rapeseed oil as fuel in diesel engines for mobile machinery has already been investigated in previous studies. It was noted that HC, CO, and particulate emissions are reduced compared to diesel fuel. At the same time, NO_x emissions tend to increase. The reason for this is the higher ignition delay of rapeseed oil, which ensures that there is more fuel in the combustion chamber before auto-ignition occurs. This increases the proportion of thermal NO_x [24].

The intention of a previous study was to develop a rapeseed oil-diesel tractor concept that complies with the EU Stage IIIb and IV emissions regulations. Here, the focus was on determining the mixture ratio of both fuels by means of additional sensors. Subsequently, characteristic diagrams were created for defined mixtures to adapt the engine control to the mixture. Differences in performance and their effect on pollutant emissions were also investigated when operating with rapeseed oil fuel [16,17].

In [13], the soot emission behaviour of a diesel engine in rapeseed oil operation was investigated. For this purpose, the loading cycles of the diesel particulate filter in diesel and rapeseed oil operation were compared. The active DPF regeneration in rapeseed oil operation was also investigated. The result of the study shows that active regeneration through fuel post-injection leads to dilution of the engine oil through heavy fuel input. As an alternative to engine-internal regeneration measures, a catalytic burner was tested.

[25] also investigated active DPF regeneration in rapeseed oil operation. Here, a variation of injection and exhaust throttle position was used to increase the temperature in the exhaust gas. A high-idle operating point was selected for the measures. This will be discussed in more detail in the following, as these results will be taken up.

5. Setup of the Experiment

The experiment was conducted on a John Deere 4045 engine. This is a 4-cylinder in-line engine for NRMM (non-road mobile machinery) applications. It has two series exhaust gas turbochargers, a cooled external EGR line and a common rail injection system with solenoid valve injectors. In our test bench configuration for vegetable oil use, the engine achieves a maximum power of 110 kW @ 2100 rpm and a maximum torque of 580 Nm @ 1600 rpm. Further technical data of the test engine are listed in Table 1. The system is designed to comply with EU stage V emission standard (limits are listed in Table 2). The exhaust aftertreatment system includes a DOC (diesel oxidation catalyst), a DPF (diesel particulate filter) and an SCR catalyst (selective catalytic reduction) with upstream urae dosing system and downstream ASC (ammonia slip catalyst).

Table 1: Technical details of test engine

	value	**unit**
maximum effective power	110	kW
maximum torque (@1600 rpm)	580	Nm
nominal speed	2100	rpm
displacement	4.5	dm^3
compression ratio	17.3: 1	-
bore diameter	106.5	mm
stroke	127.0	mm
firing order	1-3-4-2	(cyl. no.)
valves per cylinder	4	-
emission standard	EU stage V	-

Table 2: EU Stage V emission standard [Norm einfügen]

	56 kW ≤ P < 130 kW
CO (g/kWh)	5.0
HC (g/kWh)	0.19
NO (g/kWh)	0.4
PM (g/kWh)	0.015
PN (#/kWh)	1×10^{12}

The tests were performed using the original ECU. The most important variables which were adapted are the position of the exhaust throttle valve, the position of the EGR valve and the fuel injection. With the current configuration, it is possible to carry out up to five injections per cycle. For all five injections, the timing can be modified, and for four of the injections, the injected quantity can be adapted. The access to the injection quantity of the fifth injection must remain available to the ECU for load control. In addition to the time and quantity, the injection pressure can be adjusted. The maximum injection pressure of the system is 220 MPa.

Five different fuel mixtures were used to carry out the experiments. Rapeseed oil and diesel fuel were mixed in increments of 25 %. An overview of the fuel mixtures and their designations is given in Table 3. The nomenclature of the investigated engine operations is explained in

Table 4.

Table 3: Fuel mixtures of the experiment

Name of fuel mixture	Description
R0	100 % (m/m) diesel fuel – corresponding to DIN EN590 standard: 93 % (m/m) fossil diesel, 7 % (m/m) biodiesel
R25	25 % (m/m) rapeseed oil fuel (DIN 51605) and 75 % (m/m) diesel fuel (DIN EN590)
R50	50 % (m/m) rapeseed oil fuel (DIN 51605) and 50 % (m/m) diesel fuel (DIN EN590)
R75	75 % (m/m) rapeseed oil fuel (DIN 51605) and 25 % (m/m) diesel fuel (DIN EN590)
R100	100 % (m/m) rapeseed oil fuel (DIN 51605)

Table 4: Nomenclature of the measurements

Measurement	Description
standard app.	reference measurement of series engine application
exEGR deac.	deactivation of external EGR; each further measurement is performed with deactivated external EGR
max. throttling	minimum exhaust throttle flap position; determined by rise of soot concentration
late timed single inj.	late single injection
pre inj. + late timed main inj.	single pre-injection with late main injection
dbl pre inj. + late timed main inj.	double pre-injection with late main injection
throttling + late timed single inj.	minimum exhaust throttle flap position with late single injection
throttling + pre inj. + late timed main inj.	minimum exhaust throttle flap position with single pre-injection and late main injection
throttling + dbl. pre inj. + late timed main inj.	minimum exhaust throttle flap position with double pre-injection and late main injection

6. High Idle DPF Regeneration with Share of Vegetable Oil

To develop the high idle regeneration for the use of vegetable oil fuels, various internal engine measures were investigated to increase the exhaust gas temperature. Throttling the exhaust gas mass flow and late timed center of combustion are suitable to increase the exhaust gas temperature, without post-injection or mechanical modifications. Mechanisms were developed for implementing the latest possible timing for the center of combustion. Figure 4 gives an overview of the results of the study.

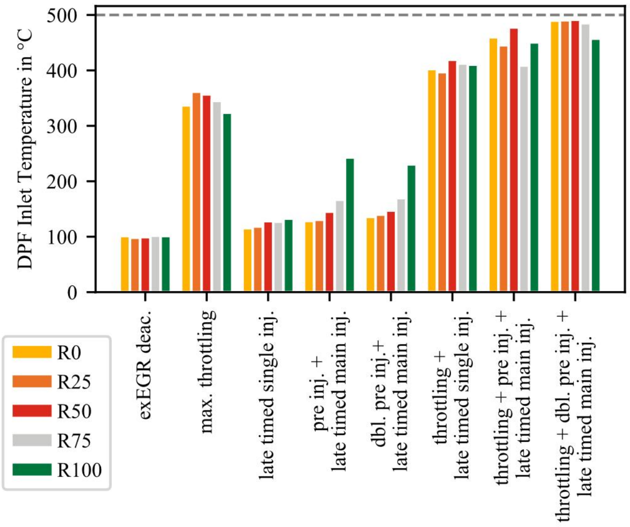


Figure 4. Comparison of reachable exhaust gas temperatures of different engine measures in high idle operation

As it can be seen, throttling has the biggest impact on the change in exhaust gas temperature. When shifting the center of combustion, a significant increase in exhaust temperature can only be achieved with pre injection and double pre injection and the use of pure rapeseed oil. The heat release shows that the start of combustion does not change with increasing rapeseed oil content, but the end of combustion occurs later. Thus, the end of combustion of R100, dbl. pre inj + late timed main inj. is approx. 10 °CA after the end of combustion of D100, dbl. pre inj. + late timed main inj. (with the same injection start). One reason can be found in the lower energy density of rapeseed oil, so that it can be assumed that the injection process takes longer, and more exhaust heat is available when the exhaust is opened. The pre-injection or double pre-injection compensates the wall heat losses in compression near TDC without contributing to the work of the engine. The boundary condition for ignition of the main injection is thus maintained for longer. By combining throttling and double pre-injection with late main injection, the highest exhaust gas temperatures can be achieved. More detailed information on the mechanisms of the measures can be found in [25].

Under these boundary conditions, the regeneration was tested with the result that a fully loaded particle filter can be completely freed of soot within 20 minutes. The complete procedure of the regeneration test is also described in [25].

With the newly developed regeneration strategy, engine oil dilution with vegetable oil can be almost completely prevented. Figure 5 compares the engine oil dilution with conventional regeneration with vegetable oil with the engine oil dilution with the new high idle regeneration.

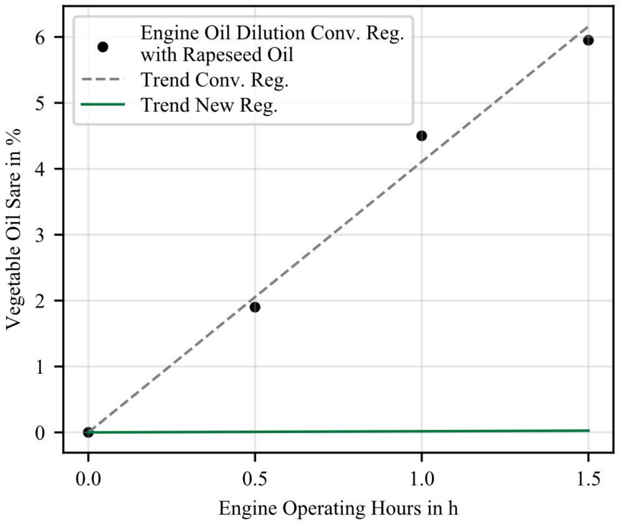


Figure 5. Comparison of engine oil dilution with conventional regeneration and new high idle regenration for the use of rapeseed oil

With conventional regeneration a dilution rate of 4 %/h is achieved [13]. Trough the new high idle regeneration, this can be reduced to 0.02 %/h. This means that the oil service interval for diesel operation will be maintained with rapeseed oil fuel.

7. DPF regeneration in part-load operation

For regeneration in high idle operation, pure rapeseed oil fuel is the most critical case for thermal DPF regeneration regarding engine oil dilution. To reduce the scope of the measurement series, the partial load regeneration was primarily investigated with pure rapeseed oil. Three different load points were chosen at a constant speed of 1800 rpm and 50 Nm, 100 Nm, and 200 Nm. The aim of the investigation is to find a suitable regeneration strategy for transient vehicle operation by combining regeneration in high-idle operation and regeneration in partial load.

To increase the exhaust gas temperature, the same measures are used in the part-load range as in the high-idle application. Figure 6 shows the temperatures at the DPF inlet when the external EGR is switched off compared with the basic application.

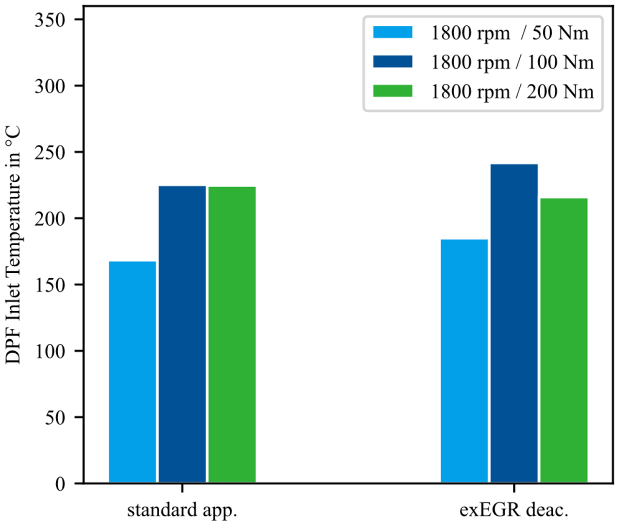


Figure 6: Comparison of the change in exhaust gas temperature caused by deactivating the external EGR at 50, 100 and 200 Nm (1800 rpm)

As can be seen in the diagram, the effect of exhaust gas recirculation on the exhaust gas temperature differs within the various operating points. At the two lower load operating points, the exhaust gas temperature increases without EGR, while at the 200, the temperature drops. To be able to exclude the influence of the EGR on the temperature, the EGR was switched off for the following measurements.

With the variations in injection and exhaust throttle position, the exhaust gas temperature at the DPF was significantly increased. An overview of the exhaust gas temperature at the DPF inlet for the three load points is shown in Figure 7.

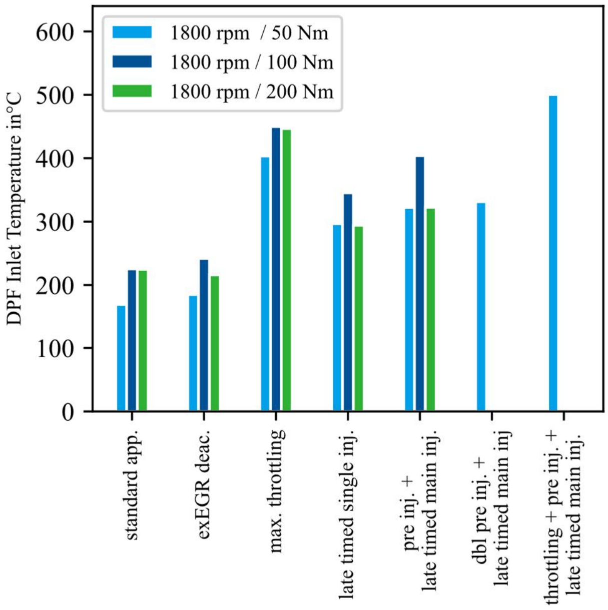


Figure 7: Reachable exhaust gas temperature of the investigated measures at 50, 100 and 200 Nm

As in the case of the previously described high-idle regeneration, the measurement can be divided into two parts. In the first part, the closing of the exhaust throttle (max. throttling) and the variation of the injection are considered (late timed single inj., pre inj. + late timed main inj., dbl. pre inj. + late timed main inj.), second part the combination of both (throttling + pre inj. + late timed main inj.,). Since the combustion retarded by the variation of the injection reacts with a significant temperature change to a change of the air-fuel ratio (caused by the closing of the exhaust throttle), the combination was tested only at the low load point (50 Nm) for reasons of component protection of the exhaust turbocharger group. Double pre-injection with late timed main injection was also dispensed with at the higher load operating points due to the increased cylinder outlet temperature. Further retardation of combustion is not possible, and compensation of wall heat losses is not necessary.

As shown in Figure 7, by closing the exhaust throttle valve, the temperature can be raised to over 420 °C at the 100 Nm and 200 Nm operating points. In both cases, the lambda value is 1.9, which corresponds to a residual oxygen content of approx. 10 % and thus sufficient oxygen is present in the exhaust gas for rapid DPF regeneration. Due to the increased charge exchange losses, the efficiency of the engine suffers because of the throttling, but regeneration mainly by means of oxygen is possible here by means of a 'simple' measure. At the 50 Nm load point, throttling alone is not sufficient to reach the 420°C and thus further measures concerning the injection are necessary. However, through a combination of closing the exhaust throttle valve and delayed main injection with pre-injection, the exhaust temperature can be raised to approx. 500°C, which is sufficient for active regeneration.

To evaluate the effectiveness of the various measures, the next step is to consider how much of the fuel enthalpy used is available for DPF regeneration in the exhaust gas. The comparison of the enthalpies is shown in Figure 8.

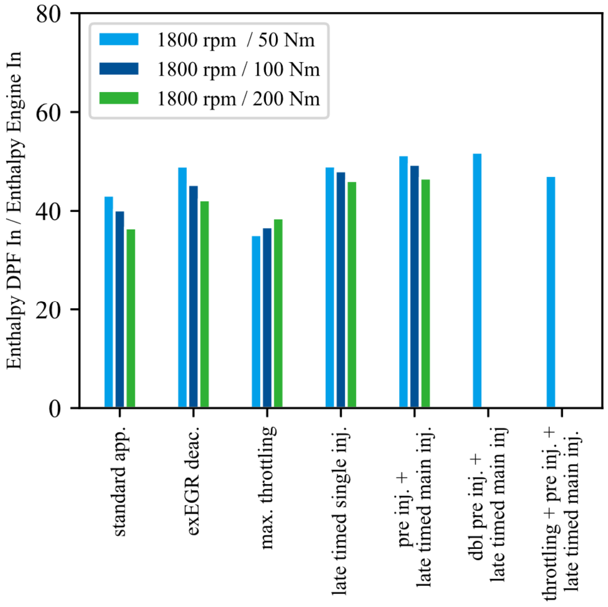


Figure 8: Fuel efficiency with focus on the increase in exhaust gas temperature

As can be seen in the figure, the enthalpy in the exhaust gas drops sharply due to the throttling of the exhaust gas mass flow in relation to the enthalpy introduced at the 50 Nm load point, despite deactivation of the external EGR. This measure makes the lowest enthalpy available for regeneration. With all variations of injection, the enthalpy in the exhaust gas increases compared to the standard application. This means that more heat is available for regeneration. However, throttling is indispensable to achieve the required temperatures.

As shown in Figure 6, the external EGR has different effects on the exhaust gas temperature depending on the operating point. In the following, we will therefore investigate whether the addition of EGR can still have a positive effect on regeneration.

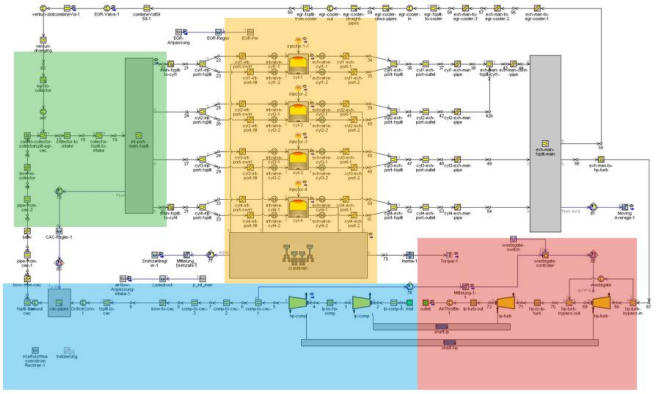
7.1 Impact of external EGR

In external EGR, the exhaust gas is extracted upstream of the exhaust gas turbocharger, cooled and fed back to the charge air. The EGR quantity depends on the pressure gradient between the cylinder outlet and the charge air path and on the electrically controllable EGR valve. Mixing the combustion gases with the fresh air increases the number of triatomic molecules, such as H_2O and CO_2, with a high specific heat capacity. Since more energy is needed to heat the air-exhaust mixture, the local peak temperature drops during combustion. Even a small decrease in peak temperature influences the engine's NO_x emissions, which can thus be effectively reduced. In addition, the exhaust backpressure reduces the amount of exhaust gas that has to be pushed out.

Since the exhaust gas is taken from the EGR before the exhaust gas turbocharger, less enthalpy is available to the turbocharger, which results in a decrease in the intake air mass flow rate. Depending on the magnitude of this decrease, it is therefore possible that, despite the increased specific heat capacity of the exhaust gas, the absolute heat capacity of the air-fuel mixture decreases, resulting in an increase in the exhaust gas temperature and thus a positive effect for DPF regeneration.

To investigate these effects, a simulation model of the engine was reconstructed using the 0D/1D simulation software GT-Power. Reference was made to the real engine components and test bench construction. The complete set-up of the model can be seen in Figure 9.

The inlet template is used to specify the initial conditions such as ambient pressure, ambient temperature, and the composition of the air. This is followed by the two-stage turbocharging and the charge air cooling. The individual components are connected via piping, which was simulated on the test bench based on real conditions. Further pipes lead via EGR mixers to the intake manifold, where the mixture is distributed to the 4 cylinders. The exhaust line runs analogous to the intake line via pipes to the high-pressure turbine and from there to the low-pressure turbine. The high-pressure turbine can be bypassed by means of a waste gate, which is permanently closed for the simulation due to the boost pressure control. The low-pressure turbine is followed by the exhaust throttle valve, the diameter of which must be specified manually. Since the exhaust gas aftertreatment is not modelled, the throttle valve is followed by the exhaust, which would correspond to the inlet of the DOC on the test bench. Initial conditions such as pressure and temperature are also specified here.



🟦 = Air section with compressor group and intercooler
🟩 = EGR-Mixxer and intake manifold
🟨 = Injectors, cylinders and cranktrain
🟥 = Exhaust gas section with turbine group and outlet

Figure 9: Engine model in GT Power

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In the cranktrain, the kinematic properties of the engine are specified. The pressure forces are also converted into a torque here. The basis for this is a geometric model of the cylinders and the masses of the rotating parts. The friction power is calculated by an adapted friction model. Data regarding heat transfer and combustion itself are defined in the cylinder objects. Each cylinder object has an injector object in which the geometric data of the injectors and the injection data are stored.

The calibration took place at the three operating points described for all variations of injection and exhaust throttle position.

To investigate the influence of EGR during regeneration, the EGR concentration was successively increased in the simulation model during the variations. In most cases, the same picture emerges regarding the change in exhaust gas temperature. The curve of the exhaust gas temperature and the lambda value is shown in 10 as representative of all variations at the operating points 1800 rpm and 50 Nm, or 100 Nm in the late timed single inj. and dbl. pre inj. + late timed main inj. application.

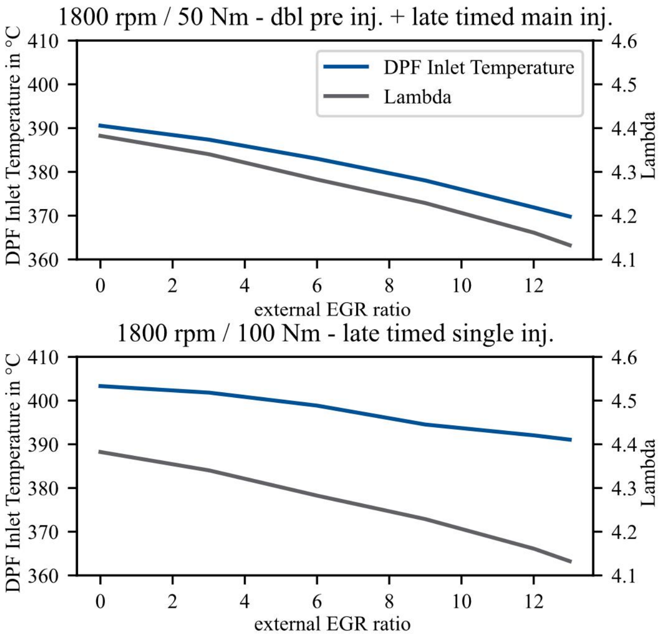

Figure 10: Impact of external EGR for the temperature increase at 50 Nm and 100 Nm

As the figure shows, the exhaust gas temperature decreases with increasing EGR concentration, as does the lambda value. In these cases, no positive effect for regeneration can be achieved by means of EGR. An opposite effect can be seen with the addition of EGR at the operating point 1800 rpm / 200 Nm (11).

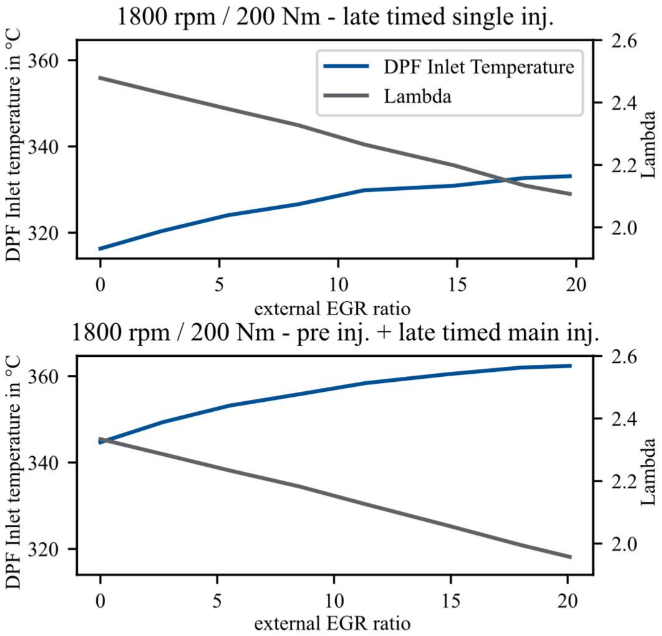

Figure 11: Impact of external EGR on the temperature increase of different measures at 200 Nm

he use of EGR during regeneration can therefore be considered reasonable at this operating point. Fuel savings of up to 0.6 kg/h can also be achieved in the two applications by EGR. However, the temperature increases of max. 30 °C are rather small compared to the fluctuations of the injection.

Since the temperature could only be increased at one load point, the increase is rather small compared to other applications, and the possibility of a combination with other measures is excluded by lowering the lambda value, the EGR plays a subordinate role in DPF regeneration.

8. Summary and Conclusion

By operating an internal combustion engine with pure rapeseed oil fuel, CO_2 emissions can be reduced by up to 58 %. This operation requires adjustments to the fuel system and engine control system. Diesel particulate filter regeneration is particularly challenging, as it is not possible to rely on post-injection into the push-out cycle, like it is the case with conventional diesel fuel.

In the study described above, measures to increase the exhaust gas temperature were investigated regarding their suitability for DPF regeneration. In this context, various mixtures of diesel and rapeseed oil were investigated in high-idle operation, as well as pure rapeseed oil fuel in part-load operation. In both cases, it was possible to generate temperatures of more than 420 °C at the DPF inlet and thus find suitable applications for regeneration in transient engine operation with pure rapeseed oil fuel in an appropriate time interval. Also, the measures taken in high-idle operation did not lead to dilution of the engine oil with rapeseed oil, which is necessary to integrate the regeneration process into real engine operation

It also became clear that the influence of the external high-pressure EGR on the exhaust gas temperature differs greatly depending on the operating point. The influence of EGR on regeneration was investigated using a 0D/1D simulation model. By adding EGR during regeneration, it was found that in most applications the exhaust gas temperature drops. Only at the 200 Nm operating point was it possible to detect a temperature increase of approx. 30 °C at an acceptable lambda value with a fuel consumption benefit, but this is not sufficient for active DPF regeneration. Due to the lowering of the lambda value, the addition of EGR limits the combination with other measures, so that EGR with the current possibilities does not play a role during DPF regeneration.

In future studies, regeneration with the addition of EGR could be investigated using intelligent boost pressure control. By adjusting the air mass flow, the heat capacities of the air/fuel mixture could be specifically influenced to achieve a consumption advantage with increasing exhaust gas temperature.

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Definitions/Abbreviations

EU	European Union
CO_2	carbon dioxide
CO	carbon monoxide
DPF	diesel particulate filter
DIN	German industrial standard
DOC	diesel oxidation filter
ECU	electronic control unit
EGR	exhaust gas recirculation
EN	European standard
HC	hydrocarbons
HVO	Hydrogenated vegetable oils
NO_2	nitrogen dioxide
NO_x	nitrogen oxids
RME	Rapeseed oil methyl ester
O_2	oxygen