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Exhaust gas recirculation with highly oxygenated fuels in gas turbines

Žiga Rosec[a], Tomaž Katrašnik[a], Urban Žvar Baškovič[a], Tine Seljak[a,*]

[a] Faculty of Mechanical Engineering, University of Ljubljana, Aškerčeva cesta 6, 1000 Ljubljana, Slovenia

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ABSTRACT

To achieve a near zero emission footprint of combustion in power generation, introduction of fuels with low global warming potential, namely low-carbon or carbon neutral fuels and simultaneous reduction of harmful emissions through implementation of advanced combustion concepts is necessary. The study addresses this challenge experimentally by proposing a new approach which combines the benefits of highly oxygenated waste derived fuels, here represented by glycerol, and an introduction of external exhaust gasses recirculation (EGR) aimed for further reduction of NO_x emissions. Thus, the recognized role of the high oxygen content in glycerol can positively influence the well-known penalties of EGR, which are commonly perceivable through elevated CO and soot emissions. The measurements were performed with an experimental gas turbine equipped with an exhaust heat regeneration system and feedback loop for 8% and 13% EGR content in compressor intake air. The proposed system layout represents a technically viable and cost-efficient approach for upgrading existent gas turbine setups with a goal to improve their emission footprint. Results confirm that with 8% and 13% EGR rate, NO_x, CO and soot can be reduced simultaneously, thus improving the CO- NO_x and soot- NO_x trade off approximately 2-fold for each species. Additionally, underlying phenomena responsible for observed improvements while increasing EGR rate are identified as an increased soot reactivity, a competing effect of EGR related dilution and an increased primary air temperature together with spray related parameters linked to low stoichiometric ratio of glycerol.

1. Introduction

Although the advances in exploitation of fully renewable energy sources are consistently paving the way towards defossilized future [1], all relevant energy scenarios predict a significant contribution of combustion-generated energy in stationary applications as well as in sea and land mobility [2]. To minimize the negative impact of combustion, the following prerequisites have to be met:

- switching from fossil to renewable fuels featuring low global warming potential based upon their life cycle assessment (LCA) and thereby effectively contributing to reduction of global CO_2 [3].
- reduction of harmful emissions through implementation of advanced combustion concepts with the aim to minimize trace contaminants (i.e. NO_x and particulate matter (PM)).

To meet the 1st goal set above, a wide pallet of renewable and waste derived fuels is available, however they often exhibit unsustainable business cases and suboptimal LCA performance [4]. To meet both criteria, unrefined fuels originating from waste, residuals and side streams, are an attractive option for stationary power generation since they feature low costs in terms of €/kWh [5], are often considered as CO_2 neutral [3] and can often exhibit notable advantages in terms of NO_x and PM emissions as was previously shown by Seljak et al. [6].

The available data suggests that already by selecting appropriate fuels and performing suitable adaptations of power generation systems, significant reduction of pollutants can be achieved besides reduction of CO_2 emissions that arises from usage of bio-based residuals, where oxygenated fuels feature the biggest advantage. Already in a study by Verma et al. [7] oxygen function groups played a vital role in the reduction of soot particles, whereas other studies confirmed a beneficial impact of blending conventional fuels, such as jet-A fuel [8] with other oxygenated fuels like biodiesel [9] or ethanol [10].

The most promising results were recently achieved with glycerol,

Abbreviations: CO, carbon monoxide; CO_2, carbon dioxide; CC, combustion chamber; D2, diesel fuel; EQR, equivalence ratio; EGR, exhaust gas recirculation; GLY, Glycerol; LCA, life cycle assessment; LHV, lower heating value; MSS, micro soot sensor; NO_x, nitrous oxides; O, Oxygen; PM, particulate matter; PAT, Primary air temperature; TIT, Turbine inlet temperature

* Corresponding author.
E-mail addresses: Ziga.Rosec@fs.uni-lj.si (Ž. Rosec), Tomaz.Katrasnik@fs.uni-lj.si (T. Katrašnik), Urban.Zvar-Baskovic@fs.uni-lj.si (U. Žvar Baškovič), tine.seljak@fs.uni-lj.si (T. Seljak).

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Table 1
Properties of technical glycerol, crude glycerol from biodiesel industry and the reference fuel D2.

	Technical grade glycerol [6]	Crude glycerol (from biodiesel industry) [20]	Diesel [6]
C (wt%)	42.19	/	87.00
H (wt%)	9.14	/	13.00
N (wt%)	0	0.014–0.078	0
S (wt%)	0	/	< 0.001
O (wt%)	48.67	/	0
Glycerol content (wt%)	99.84	50–87	/
NaCl content (wt%)	/	0.2–5.47	/
Ash content (wt%)	0.0002	0.93–6.34	/
Water content (wt%)	0.03	8.16–43.42 [21]	/
Density (kg/L)	1.26 at 20 °C	1.0181 at 20 °C	0.82–0.845 at 15 °C
LHV (MJ/kg)	16	/	42,2
Stoch. Ratio	5.19	/	14,7

which proved to significantly contribute towards reduction of NO_x and soot emissions, what was attributed to the role of oxygenated groups being available in the early stages of the flame. Seljak et al. [6] achieved a 5-fold reduction of absolute NO_x concentration with glycerol fuel compared to a standard diesel fuel (D2) with no dependence on turbine inlet temperature (TIT) and a 10-fold reduction of soot particles with a strong dependence on TIT. The study also lined out the phenomena responsible for reduced soot and NO_x emissions, pointing out that a major contributor are concentration-driven effects in the spray zone, where stoichiometric ratio is the main factor for obtaining promising results as it enables to achieve lower concentration of nitrogen within the flame.

Based on the upper findings, highly oxygenated fuels might, due to a very early availability of reactive oxygenated species during combustion, exhibit a lower sensitivity to EGR, hence inclusion of EGR could further promote the reduction in NO_x while having a reduced penalty on CO and soot emissions. The 2nd goal set above could thus be fulfilled by incorporating an EGR to highly oxygenated carbon neutral fuels.

In the area of gas turbines and micro gas turbines using EGR, there is number of studies available. Røkke et al. [11] found that EGR reduces the flame temperature. Hasemann et al. [12], Evulet et al. [13] and Best et al. [14] individually experimented on what rates of EGR are possible and observed consequent NO_x emission reduction while CO and other emissions increased. These findings were also confirmed by Bellas et al. [15] who used selective EGR. Simulation studies like that of Giorgetti et al. [16] and Li et al. [17] have shown a new use for EGR, as the higher CO_2 concentration in flue gases increased the electrical efficiency of the combined gas turbine and carbon capture plant. Cameretti et al. [18] showed that with high external EGR rate, it is possible to obtain conditions, resembling MILD combustion. Particularly these last, distributed combustion regimes are the only ones that do not introduce penalties to combustion efficiency while they effectively reduce NO_x emission formation. Unfortunately, these regimes require extensive adaptations and numerous practical challenges are still to be resolved.

It is therefore obvious that regardless of all EGR advantages on combustion there are still drawbacks presented by the aforementioned studies where NO_x-soot and NO_x-CO trade-offs are present. The current study is addressing this challenge by targeting the synergistic effects of EGR and highly oxygenated fuels and is aiming to reduce the NO_x emission while minimizing the penalty on CO and soot.

In order to maximize practical potential of the proposed approach, the objective of this study is to confirm the feasibility of inclusion of external EGR in existent micro and small gas turbines. This offers a low-cost and technically viable approach, since most of such systems already incorporate exhaust gas heat regeneration and exhaust gas heat recovery, making the temperatures of the exhaust gas suitable for direct feeding to compressor intake. After setting up suitable experimental system, specific objectives of the study can be realized:

- Developing a platform for investigating different external EGR rates in experimental gas turbine, using glycerol as a representative of highly oxygenated fuels.
- Identifying the underlying phenomena for altered emission formation mechanisms, particularly in the area of NO_x and soot.
- Analysing the trade-off between CO-NO_x and soot-NO_x relations that are driven by EGR related influences and providing recommendations for further optimization.
- Identifying the potential to implement external EGR as a drop-in approach to existent microturbine setups by relying on comprehensive analysis of combined effects of different emission species.

The main outcomes thus offer a first analysis and guidelines for further reducing the environmental impact generated by existent decentralized power generation systems that are based on microturbine technology and offer an excellent platform for low-cost and technically feasible upgrades without compromising the stability of energy supply.

2. Materials and methods

Within this section, the detailed experimental approach is presented along with control strategy and fuels used. Approach to evaluation of emission performance and representation of realistic environmental impact is given as well.

2.1. Fuel conditioning

Although the biggest environmental advantage could be achieved with crude glycerol from biodiesel production, which is considered to have zero CO_2 footprint in RED II directive, the study focuses on investigation of technical grade glycerol to isolate the benefits of highly oxygenated fuels and provide a basis for utilization of wide variety of highly oxygenated bioliquids (i.e. liquefied wood, pyrolysis oil, HTL biocrude) that represent waste, residual or side streams from different feedstock or industry processes [19]. Chemical and physical properties of glycerol, used here as a model compound are presented in Table 1, while comparing it with crude glycerol and D2. By using technical grade glycerol other impurities such as ash and fuel bound nitrogen do not affect emission formations which allows for a better understanding of emission formation mechanisms.

Main challenges when utilizing glycerol in gas turbines are mainly linked to its high viscosity and lower heating value (LHV). In order to obtain a comparable combustion efficiency and similar thermodynamic parameters, the experimental system was equipped with several adaptations that were already addressed previously [6]. The key improvements comprise:

- a fuel preheating line for lowering the glycerol viscosity,
- appropriate nozzle type for sufficient glycerol atomization,
- nozzle thermal protection,
- recuperator for higher primary air temperature (PAT).

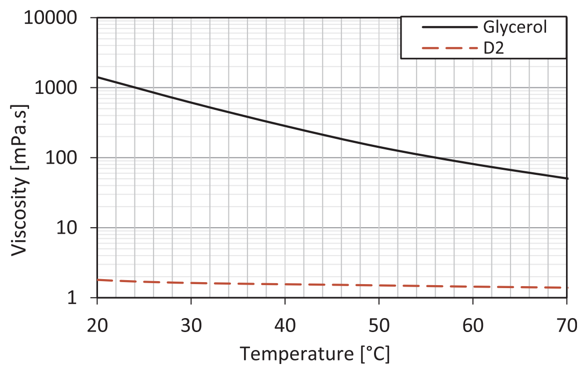

Fig. 1. Temperature dependence of glycerol and D2 viscosity.

Since viscosity is one of the main factors influencing atomization it is mandatory to exploit the temperature dependence of viscosity presented in Fig. 1. By preheating the fuel to 70 °C, it is possible to obtain an order of magnitude lower viscosity of glycerol (from 1412 (mPa-s) at 20 °C to 50,6 (mPa-s) at 70 °C). Although this still exceeds the recommended limits of 15 mm^2/s [22], 12 mm^2/s [23] and 10 mm^2/s [24] for all commercially available gas turbine injection nozzles, use of air-blast and air-assist atomizers can partially solve this challenge as was already confirmed by [25] and [26]. For preheating of the fuel, fuel conditioning system is presented in Fig. 2. The set up contains two pumps, one is used to reach a homogenous temperature of the fuel, and is connected in a looped line to the heated tank and includes a filter to capture any impurities that may be present. The second pump is used to feed the fuel to the combustion chamber (CC) through mass flow meter. Temperature is being observed as well as on the first looped line as on the three-point valve connecting to the fuel feed arm in gas turbine.

2.2. Combustion test rig

Experimental gas turbine used in the study was based on a platform with a capability of modular exchange of components that allows the utilization of a wide variety of thermodynamic parameters [6,27–29]. The experimental micro gas turbines can be divided into several subsystems that have vital roles in enabling glycerol combustion. We can divide them into the fuel preheating line that was extensively described in the previous chapter. These sub-systems are presented in Fig. 3 and can be summarized as follows:

- recuperator that allows for high PAT,
- recuperator valve that allows PAT control and switching from simple to regenerative cycle,
- on-line system for switching fuel,
- twin-fluid atomizer nozzle with a thermal insulation layer,
- single can diffusive combustion chamber.

An automotive turbocharger is used for air supply and enthalpy reduction of hot gases coming from the CC. This provides a flexible experimental set up that introduces more modification options while still resembling a professional gas turbine. TIT is the main control parameter which is monitored via two K-type shielded thermocouples, more information is given by [27].

The combustion test rig is designed and used purely for combustion analyses and it aims at setting up the CC conditions that resemble those present in commercial setups to increase the transferability of the results. Different power outputs can thus be emulated by a) increasing fuel flow or b) increasing the throttle valve pressure drop after the turbine. Both approaches result in higher turbine inlet temperatures. The control strategies were extensively tested end confirmed previously [25]. Since the system is not optimized for efficiency, power output is out of the scope of key parameters required for optimization of combustion process, hence it is not measured. As the combustion test rig in its current configuration is adapted to tests with highly viscous fuels with low LHV, benchmark data with D2 are provided in configuration with no EGR to avoid unstable operation that diesel fuel exhibits in comparison to highly oxygenated fuels which are proven to operate at much lower equivalence ratio (EQR) in comparison to D2. By this, the full potential of EGR with highly oxygenated and highly viscous fuels can be demonstrated.

Engine-out emissions were measured with a portable exhaust gas analyser (Sensors Semtech-DS), which incorporates flame ionization detector for detection of THC, non-dispersive infrared analyser for detection of CO and CO_2 and chemiluminescent detector for detection of NO_x emissions. The exhaust PM emissions were measured with a portable exhaust gas analyser AVL M. O. V. E. using micro soot sensor (MSS) to detect particles with photoacoustic method, suitable for detecting particles with high light absorption coefficient. Oxygen concentrations are measured with an electrochemical oxygen sensors. The oxygen concentration in the exhaust gases is measured by sensor, embedded in exhaust gas emission analyzer and the oxygen concentration in the primary air (after EGR is introduced) is measured with a Multigas 488 analyser. Additionally, Table 2 presents the characteristic data for the gas turbine.

2.3. External EGR

Ali et al. [30] proposed that the optimum position of EGR is external and implemented before the compressor intake, as to minimize the effects on system performance. The modifications and implementation of external EGR are highlighted with a red colour in Fig. 3, also an EGR valve is fitted to set different EGR ratios. Limitations arise with the adoption of an external EGR, as compressor inlet temperatures should not be increase beyond the limits of the compressor. These vary among manufacturers of micro gas turbine setups, and range from 40 °C to 60 °C is often specified.

Higher compressor inlet temperatures also impact the effective

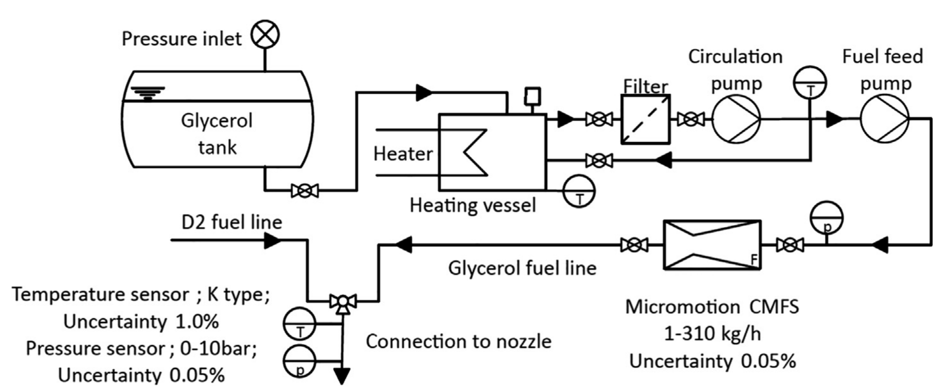

Fig. 2. Fuel conditioning system scheme.

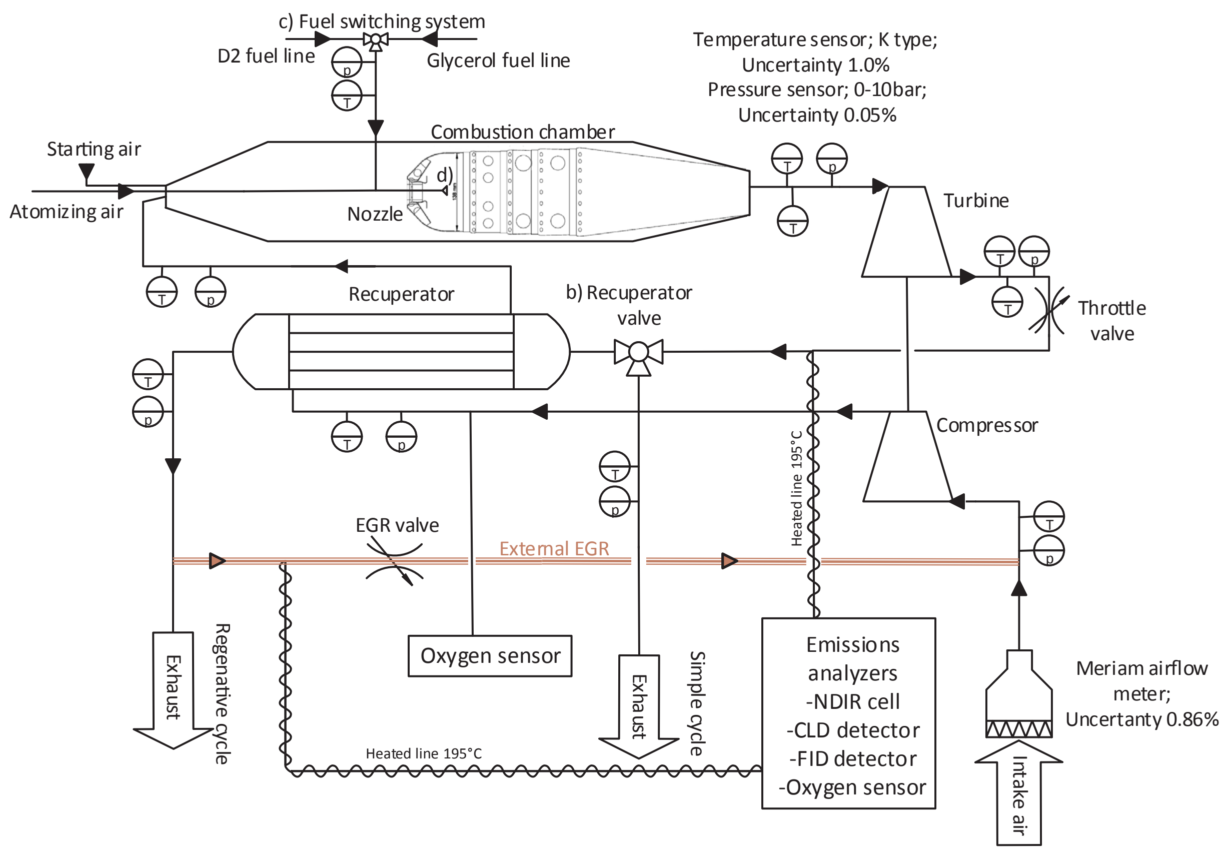

Fig. 3. Combustion test rig used with highlighted external EGR.

Table 2
Characteristic data of experimental gas turbine.

Turbine inlet temperature [°C]	700–900
Thermal power [kW]	70–240
Pressure ratio	1,7–2,5
Primary air temperature [°C]	100–600
Combustion chamber	Single can, non-premixed
Fuel type	Liquid and/or gaseous
Fuel flow [l/h]	up to 50
Fuel preheating temperatures [°C]	20–150
Injection nozzles	pressure-swirl or air-assist or swirl-air, depending on the application

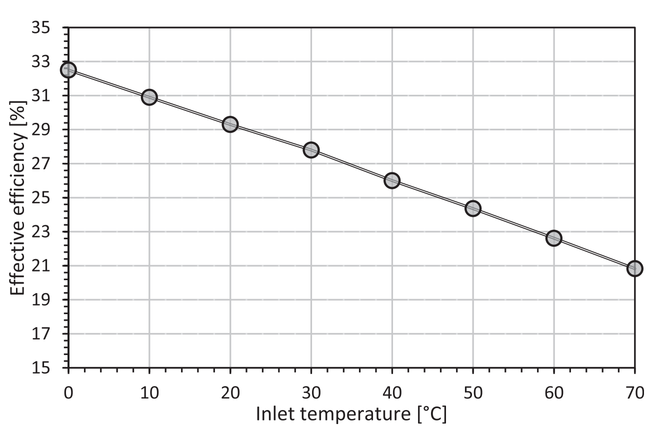

Fig. 4. Effective efficiency dependent on inlet temperature.

efficiency [31], which has to be taken into account when comparing emissions with different intake temperatures. This is done with equation (1) where concentration of each emission species (E_x) is corrected with the relative efficiency difference between the efficiency with designated EGR rate ($\eta_{EGR\ x\%}$) and the efficiency with no EGR ($\eta_{EGR\ 0\%}$). The effective efficiency dependence on intake temperature is provided from a technical description document for Ansaldo Energia T100 microturbine and is shown in Fig. 4.

$$E_{xcorected} = E_x \bullet ((\eta_{EGRx\%} - \eta_{EGR0\%}) + 1) \quad (1)$$

The EGR rate is calculated with equation (2), depending on measured oxygen concentration, $fO_{2\ air}$ is the oxygen percentage in air, $fO_{2\ exhaust\ gas}$ is the oxygen percentage in exhaust gases and $fO_{2\ air+EGR}$ is the oxygen percentage we measure in the intake air after EGR is introduced.

$$EGR[\%] = \frac{(fO_{2air} - fO_{2air+EGR})}{(fO_{2air} - fO_{2exhaustgas})} \bullet 100 \quad (2)$$

In order to compensate for the effects linked to reduced power output and reduced efficiency if external EGR is used in commercial microturbines the following correction was therefore applied to measured emission values:

- First, the emitted mass of each specific species was normalized to fuel power. This enabled the decoupling of power output and emission concentrations, hence giving a realistic insight in emission performance of operating points with external EGR.
- Second, the normalized emission mass was corrected for reduced efficiency as calculated in equation (1). This enabled decoupling of emissions from changes in efficiency, hence taking into account the required increase of fuel flow at reduced efficiency already into normalized emission mass. Although this results in little difference, the procedure was performed to provide as concise data as possible.

2.4. Testing procedure

The start of experiment was done in simple cycle to avoid the pressure drop in the heat exchanger, because of using compressed air until pilot flame was lit. D2 fuel was introduced through the nozzle, heating up the combustion rig, thus promoting self-sustained operation. When the temperatures reached their proposed values in the regenerative cycle D2 was switched to glycerol. Additionally, the fuel conditioning system was started at the start of experiment, to achieve a stable temperature of 70 °C for glycerol. The experiments were performed at different TIT that were achieved with regulating the fuel mass flow. EGR rate was controlled by manually setting the EGR valve to two different positions that resulted in EGR rates of 8% and 13% calculated with equation (1). With a closed EGR valve and no EGR present four different measurement points were made at TIT of 750 °C, 800 °C, 850 °C and 900 °C. The acquired data was averaged in the time scale of 30 s after stabilization of each operational point was achieved.

3. Results and discussion

The following chapter is divided into four subsections that evaluate the combustion process. The first analyses thermodynamic parameters in the established operational points. Second provides data on emission performance along with identification of mechanisms responsible for altered emission profiles when using highly oxygenated fuels without EGR. This baseline data, obtained with glycerol is then used as a benchmark to which results obtained with glycerol and 8% and 13% EGR rates are compared. Third segment analyses the emission formation phenomena with highly oxygenated fuels when combined with aforementioned EGR rates. The presented data are fitted with error bars based on the measurement equipment accuracy to ensure comparable representation. Finally, the interrelated effects are analysed and discussed in a fourth subsection that summarizes the feasibility of the approach together with possible future applications and improvements.

3.1. Thermodynamic parameters

A preceding study [6] showed that in spite being inherently different fuels D2 and glycerol still reach comparable baseline thermodynamic parameters, as long as differences in calorific value of the fuels are properly compensated by fuel mass flow. This is valid for all parameters relevant for combustion analysis, namely pressure ratio and primary air temperature. In order to streamline the content of the paper, these results are referred to and used in this study as a benchmark data, since benefits of glycerol in comparison to D2 were covered previously.

After introduction of external EGR, it was at first noted that external thermodynamic parameters do not exhibit reduced stability of operation. However, for successful use of external EGR it is mandatory to reduce the temperature of recirculated share of exhaust gas. In presented experimental system, this was done by exhaust gas heat recovery in primary air heat exchanger or recuperator, which effectively reduced the EGR temperature shown in Fig. 5. This shows a realistic scenario if EGR is to be implemented on existing micro gas turbines, since effectiveness of primary heat exchanger is always below 1 (typical values for micro gas turbines range from 0.8 [31] to 0.88 [32]). EGR with given temperatures then resulted in compressor intake temperature with values shown in Fig. 5. As increasing intake temperatures lower the power output of the engine, this resulted in reduced CC pressure (Fig. 6) and a moderate increase in PAT, shown in Fig. 7. Although with the increase in EGR rate the combustion regime is getting closer to the so called MILD [33] or flameless [34] combustion regimes, the presented approach allows only moderate rates of EGR, since compressor intake temperature in commercial systems is usually limited.

To compensate for the reduced CC pressure, all emission data in the section presenting emissions was normalized to mass of emission

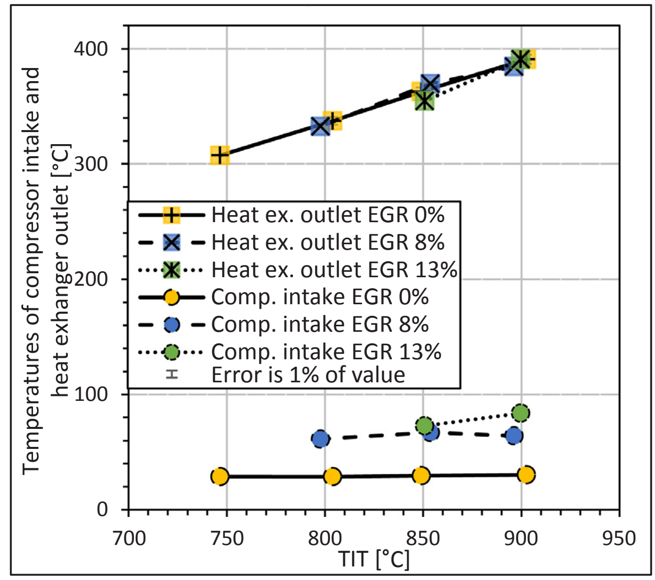

Fig. 5. Temperatures of compressor intake and heat exchanger outlet.

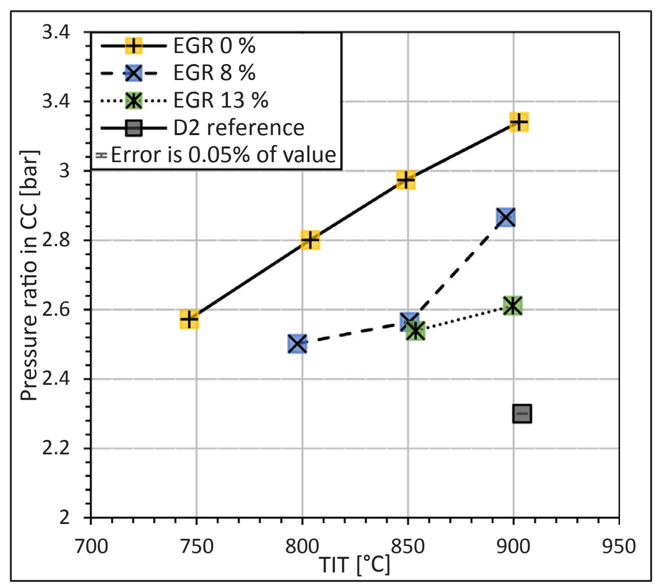

Fig. 6. Pressure ratio in combustion chamber at different operational points.

species per kWh of injected fuel. Since effective efficiency with increasing compressor intake temperature is changing as well, this effect was also included in corrected calculation. The procedure is in detail presented in 2. section and is laid out to provide an unbiased comparison of different system layouts.

Although CC pressure is inherently linked to air mass flow, the velocity field in the CC is altered as well with increasing EGR, although a compensating effect is present due to increased PAT.

3.2. Impact of highly oxygenated fuels on emission formation

A thorough investigations of oxygenated fuels such as glycerol has already been shown [6]. Up to 10-fold reduction of soot emissions and up to 5-fold reduction of NO_x emissions was achieved with glycerol, as summarized in Fig. 8 that shows the overall performance of glycerol at different fuel temperatures. Different fuel temperatures as are shown in Fig. 8 are provided to exhibit the further potential of emission reduction, since these notably impact CO emissions.

The mechanisms contributing to lower NO_x emission formation can

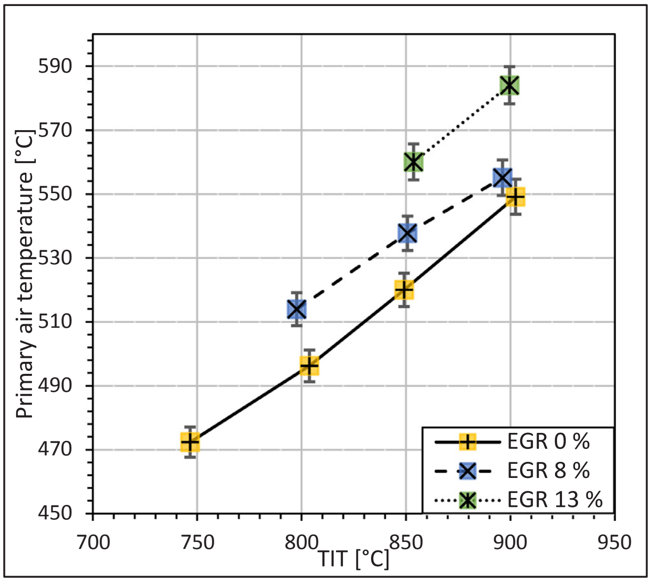

Fig. 7. Primary air temperature at different operational points.

be attributed to low stoichiometric ratio requiring less air (and less nitrogen) to achieve flammability limits what results in a 5- fold decrease in NO_x emissions compared to D2 fuel shown in Fig. 4a.

Challenging chemical and physical properties of glycerol attribute to higher CO emissions in comparison to D2 fuel as shown in Fig. 8b. The high viscosity and density impair the atomization of glycerol, resulting in larger droplets that have an increased penetration depth. With an increase of TIT as shown in Fig. 8b the CO emission formation decrease due to higher PAT and overall temperature increase.

Soot formation with glycerol fuel is more than 10-fold lower than with D2 fuel, as shown in Fig. 8c. This difference is all the greater, the higher the TIT. In our experiment soot formation strongly depends on temperature and EQR [22]. Using glycerol introduces oxygen at the rich regions of the spray core which enables earlier exothermic oxidation reactions. The temperature and EQR profile versus the O/C ratio were pointed out as the main reasons for the significantly reduced soot emissions for glycerol.

The other two mechanisms linked with lower soot emission formation can be described as inhibiting soot formation and its increased reactivity. Because of the high fuel bound oxygen radicals such as O and OH become readily available and encourage direct carbon oxidation to CO and CO_2, instead of recombination to precursors of soot. Furthermore, the fuel bound oxygen influences the formation of soot, as it was also observed by Verma et al. [7]. The formed soot particles show an increased reactivity as more oxidative points become available with the changed structure allowing soot burn off to increase in the combustion zone.

This is mostly due to lower viscosity as it helps with fuel atomization and a less heat needed for fuel vaporization, at higher TIT this aspect is less noticeable as higher temperatures are present in the CC.

In line with this baseline data, the majority of studies confirm a decrease in NO_x emissions in fuels blends that introduce fuel bounded oxygen [10,35]. These studies are mainly covering lightly oxygenated fuels such as biodiesel and vegetable oils, however the beneficial impact of bonded oxygen on NO_x and PM emission increases with oxygen content in the fuel.

3.3. EGR impact on emission formation

A major expansion of the study presented in [6] is the addition of external EGR on existing system to investigate a possibility for upgrading the existent commercial setups with EGR and highly

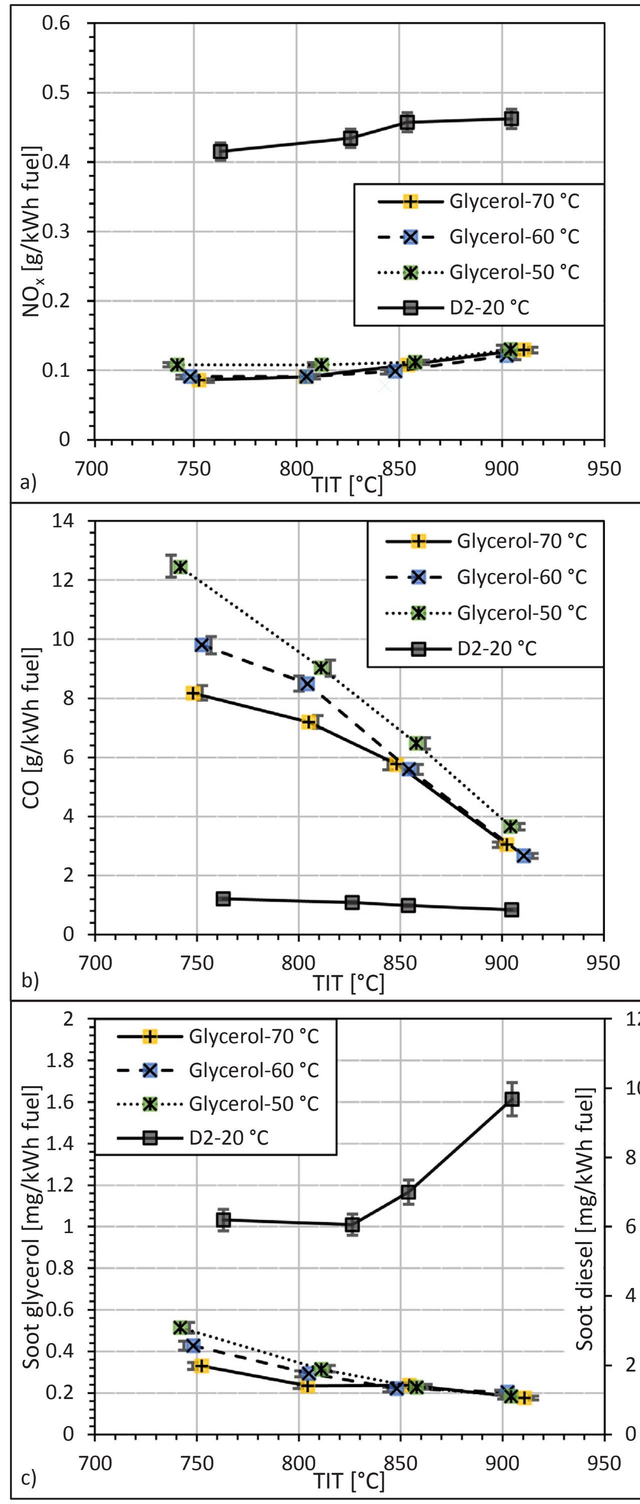

Fig. 8. Emissions comparing different glycerol temperatures to D2, a) NO_x emissions, b) CO emissions, c) soot emissions. Used as a baseline data.

oxygenated fuels. As this presents a drop-in approach, the study deliberately omitted any further improvements in the system layout. Possibilities for improvements in a system layout will be given in the following sections, while the system-level analyses are beyond the scope of this study.

To better understand the effects of EGR we can separate them into three different categories, each containing its own set of mechanisms that influence the emission formation [36].

- Thermal effect of EGR lowers the flame temperature, due to increased heat capacity of the inlet air.
- Dilution effect of EGR that lowers the concentration of oxygen and reduces the effectiveness of reactive species due to reduced collision frequency.
- Chemical effect of EGR that contains several active species such as CO_2, that participate in the combustion process, thus changing reaction pathways and equilibrium.

The following sections are focusing on each individual contaminant (CO, NO_x and soot) and analyse possible contributions of listed mechanisms in order to assess the feasibility and provide guidelines for improvement of proposed EGR implementation approach.

3.3.1. Impact on NO_x emission formation

EGR has one of the strongest capabilities to reduce the formation of NO_x emission [37]. The main mechanisms for NO_x formation can be attributed to the thermal (Zeldovich [38]) and prompt (Fenimore [39]) mechanisms, since glycerol does not contain fuel bound nitrogen. It can be assumed that little to no NO_x is formed from N_2O due to relatively low pressure ratios used in the study which are not suitable for the required three-body reaction.

Already the baseline results, obtained with glycerol without relying on EGR show that NO_x emission are very low, what was attributed to large amount of fuel bound oxygen in glycerol as lined out in section 3.2. However, by incorporating external EGR, it is possible to further reduce the concentrations as shown in Fig. 9. The reduction becomes more prominent at high TIT and high EGR rates and can be explained by the thermal effect of EGR. As exhaust gasses are recirculated, specific heat of intake air rises lowering the flame temperature in the CC [4014], thus resulting in a decrease in thermal NO_x emission formation [11]. The temperature reduction can also be linked to the high heat loss that via radiative heat transfer from CO_2 [40] that radiates heat and decreases the temperature even further. It has to be noted that simultaneously with increasing EGR, PAT is increasing as well as depicted in Fig. 7, This reveals that the underlying impact of EGR is well pronounced, since increasing PAT usually results in increased NO_x [27].

The low stoichiometric ratio of glycerol results in less air required for combustion, as mentioned before. This results in less oxygen and nitrogen entering the CC. As EGR is implied the air is further diluted resulting in decreased collision frequency [41] between oxygen and nitrogen. Additionally, EGR increases the EQR ratio especially in the primary zone, these fuel rich areas halt the NO_x emission formation as oxygen is used up for combustion reaction. The fuel type related mechanisms that prevent NO_x formation are far more dominant than EGR dilution effects, as we can see little impact with 8% EGR rates at lower temperatures (see Fig. 9).

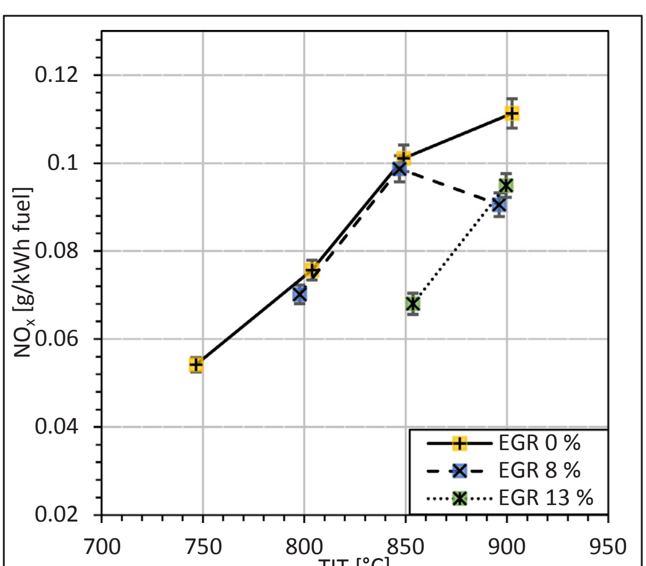

Fig. 9. NO_x emissions normalized to fuel power for different EGR rates.

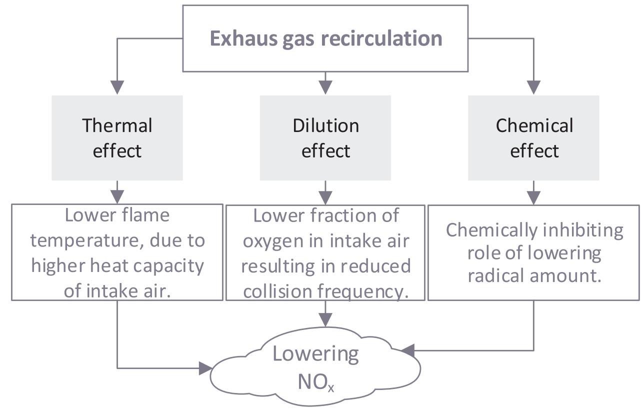

Fig. 10. Mechanisms responsible for lowering NO_x emissions formation.

It is possible to further increase EGR dilution effect with higher EGR rates that could lead to achieving even lower NO_x emissions at low TIT. The high oxygen concentration in glycerol, could enable further increase in EGR rates, which would increase all the beneficial effects including the chemical effects of EGR on NO_x emission prevention. Although the chemical effects of EGR are small, the active species play a crucial role in inhibiting and reducing the amount of radicals that prevent NO_x formation [11].

The discussed effects that are responsible for moderate lowering of NO_x emissions while relying on external EGR can therefore be summed in Fig. 10.

3.3.2. Impact on CO emission formation

It is well known that EGR tends to increase CO emissions, so at least minor negative effect of EGR was expected in present study. CO emissions production is associated with a limited residence time and lower temperatures in the dilution zone [13], which is usually associated with fuels physical and chemical properties. High viscosity and density inhibit the atomization ability resulting in poor fuel and air mixing, resulting in formation of large droplets that have a long penetration length before the mixture reaches the flammability limit. Before the combustion processes can be completed, the reactants derive to the diluting zone where reaction quenching occurs [22]. As can be seen in Fig. 11, the CO emissions decrease with the increase in TIT, since penetration length of glycerol droplets shortens and mixture is prepared earlier in comparison to lower TIT. This is in line with the results obtained in other studies.

Contrary, data shown in Fig. 11 shows that when relying on external EGR, the CO is further reduced with increasing EGR rate. The reduction at 13% EGR is 3-fold compared to 0% EGR, when emissions are normalized to fuel flow and possible effective efficiency reduction is taken into account as lined out in 2. Although the CO emissions are still higher than with conventional fuels, the shown three-fold reduction directly shows the benefits of incorporating external EGR. The reason for this was traced back to the fact that increasing external EGR rate simultaneously increases PAT, due to the reason that exhaust gas heat regeneration effectiveness is always below 1. Hence, compressor intake temperature is elevated as well, leading to higher temperatures on the CC intake.

High PAT helps with at high auto-ignition temperatures (370 °C) and high boiling point (290 °C) of glycerol. At higher PAT, glycerol vaporizes faster and the combustion starts earlier, providing enough time for complete combustion to take place before the reactants enter

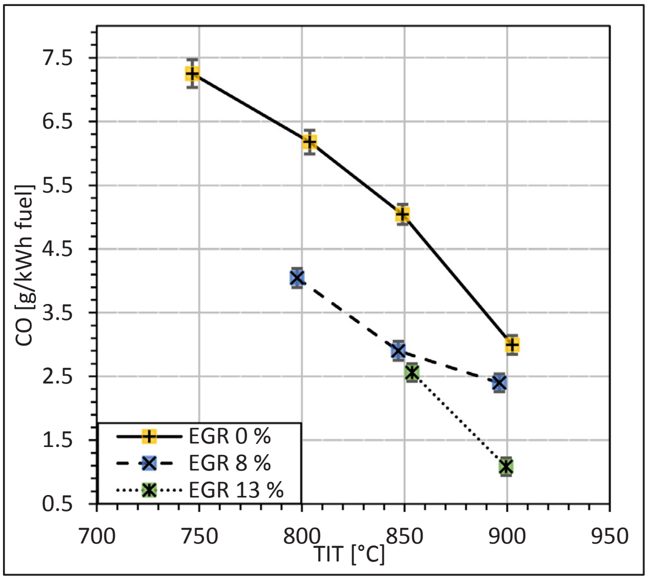

Fig. 11. CO emissions normalized to fuel power for different EGR rates.

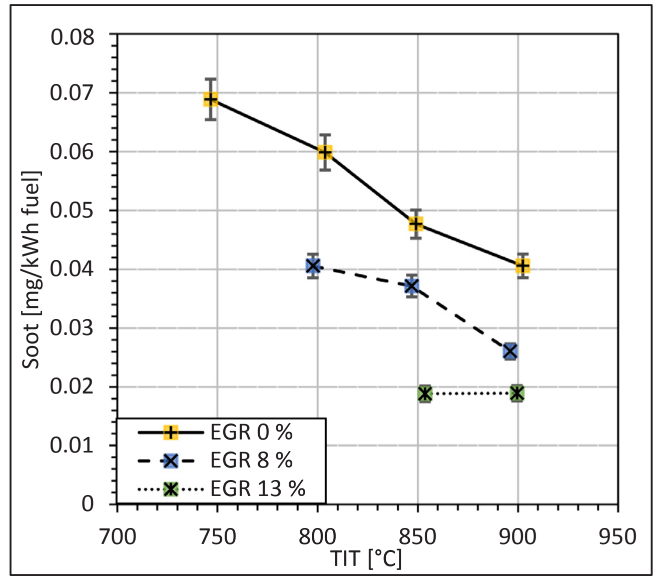

Fig. 13. Soot emissions normalized to fuel power for different EGR rates.

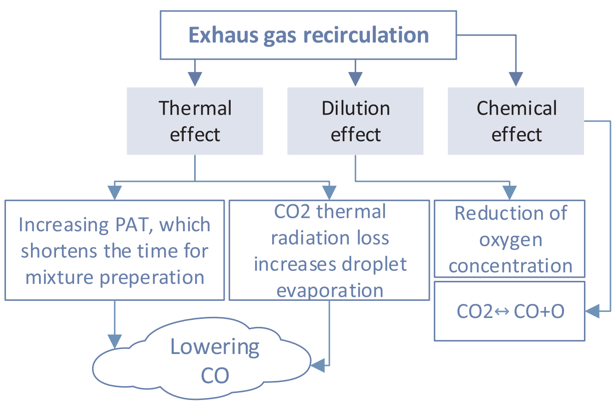

Fig. 12. Mechanisms responsible for lowering CO emissions formation.

the dilution zone. Even the mixture entrapment in liner cooling air is less severe, since the highest temperatures of inlet air lessen the reaction quenching. The overview of mechanisms, impacting the CO formation when EGR is introduced is given in Fig. 12.

The thermal effect of EGR is important as well. As EGR rises, the amount of CO_2 increases. CO_2 has a high radiative heat release [40] and this can contribute to faster mixture preparation since droplets are exposed to intensified heat transfer.

The dilution effect of EGR has no significant impact on CO emission formation as the decrease in oxygen concentration at moderate EGR rates in inlet air is offset by fuel bound oxygen. With other studies involving EGR the reaction times are slower emphasizing the lack of oxygen and resulting in CO emission formation [42].

Temperatures of CC intake air [29] are higher than the dissociation temperature, so possible dissociation can occur very early. Although, Marsh et al. [43] indicated that an increase in CO emission formation is less affected by CO_2 dissociation and more likely caused by the aforementioned effects of incomplete combustion. The resulting effect of early thermal break down of the glycerol results in flame being present in regions close to the nozzle, thus supplying heat other than PAT used for mixture formation.

At this stage it is already possible to see the synergistic effects of simultaneous NO_x reduction and CO reduction as well. Although the NO_x reduction is moderate, the CO exhibits very promising response to inclusion of partially cooled EGR in compressor intake air, hence further enabling the use of highly oxygenated and highly viscous fuel in gas turbines.

3.3.3. Impact on soot emission formation

A generally observed trend across the literature is that soot emissions increase with EGR rate. As previously shown [6], solely the use of oxygenated fuel already reduces the soot emission for an order of magnitude. The underlying reasons can be traced back to three different contributions as was pointed out in [6]:

- altered oxygen concentration profile during mixture preparation,
- prevention of soot precursor formation,
- promotion of soot oxidation reactions.

When comparing the data from 0% EGR to points with 8% and 13% EGR in Fig. 13 it is visible, that although the EGR rate is increasing, soot emissions are reducing two-fold at highest TIT and 13% EGR. This follows similar trends, as for CO emissions and again confirms that oxygenated fuels behave differently when EGR is introduced. To systematically analyse the contributions of each of the above points to the reduction of soot emissions, it is necessary to line out the phenomena which are pronounced when EGR is introduced:

- Concentration conditions of soot zone formation are altered.
- Lowered flame temperatures decelerate the reactions responsible for soot formation. The concentration of hydrogen radicals is reduced, resulting in reduced production of polycyclic aromatic hydrocarbon and soot surface growth by the hydrogen-abstraction-carbon-addition mechanism [44]. This leads to soot structure that has an increased fraction of active sites for oxidation as well as a structure that favors oxygen attack due to its changed geometry [45]. Additionally, lower flame temperature affects the soot formation by resulting in different soot nanostructure which exhibits higher reactivity due to higher H/C ratios [46].
- Lowered collision frequency, due to the lack of reactive species such as oxygen resulting in deceleration of reactions and less developed soot which exhibits higher reactivity [36].
- Chemical effect of active species like CO_2 lower soot formation and at the same time increases the soot reactivity.
- The increased reactivity of soot enables soot burn of as it enters the secondary zone of CC.
- Soot particle burns in a dual burning mode with slow surface and

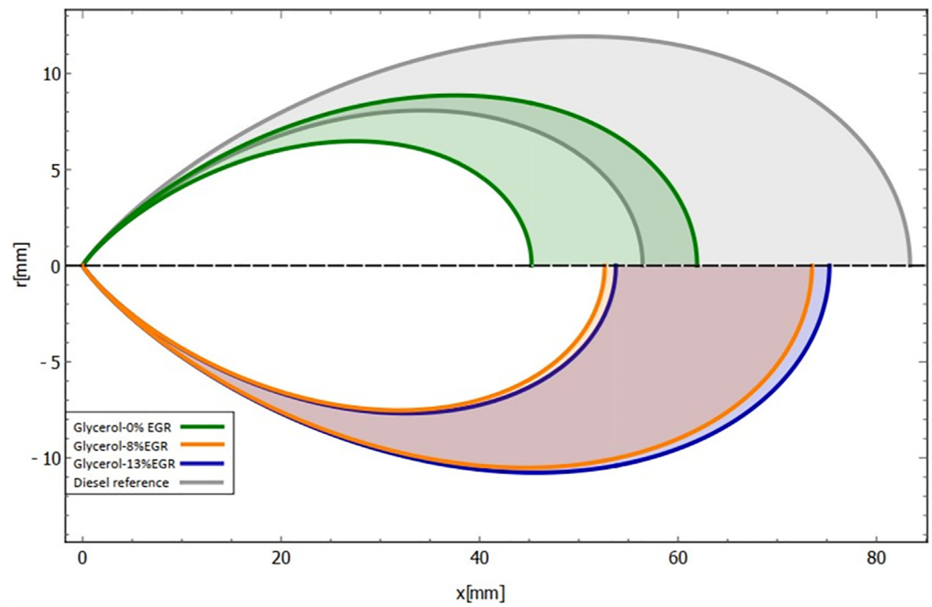

Fig. 14. Soot zone formation (centerline cross-section) within the spray with different fuels and EGR ratios. Chart origin represents point of injection, shaded areas represent volume of mixture within soot formation limits.

fast internal burning.

To analyse the first point in more detail it is necessary to plot the spray concentration profiles that take into account reduced stoichiometric ratio of the fuel. This is presented in Fig. 14, where upper and lower soot formation limits are plotted for each of the operating regimes (0% EGR, 8% EGR and 13% EGR). Local EQR ratios enveloping soot formation limits were calculated on mechanistically based 0D spray model [47] which calculates the local EQR in spray cloud and takes into account fuel stoichiometric ratio. The main assumptions, important for interpretation of calculated data in the presented case are that the momentum in-flux is only through the fuel injected from the nozzle and the spray is circumferentially symmetrical along the axis of the nozzle. At any distance from the nozzle, the spray velocity exhibits a Gaussian distribution around the centreline. Soot formation limits were set for EQR between 1.8 and 2.9 for all fuels what is sufficient to schematically depict the effects of oxygen content in the fuel.

The shaded area between the lines of each fuel represents the soot formation zone. Due to large fraction of oxygen introduced with fuel when using glycerol, less air entrapment is required to surpass the soot formation zone. In case of diesel fuel which is given as a reference, larger volume of the spray is within soot formation limits, hence residence time of the mixture where soot can form is longer.

Taking advantage of this effect with oxygenated fuels it is clear that when increasing EGR, the volume of the mixture within soot formation limits gradually increases when EGR is introduced. The margin that is present to diesel fuel effectively means that EGR can be increased even further before similar conditions as with diesel fuel are met. Hence, it is expected that oxygenated fuels could operate with significantly higher EGR rate than conventional fuels. This is also one of the main reasons that with external EGR, when also PAT increases, the PAT effect prevails over the dilution effect and cumulatively reduces soot emissions.

3.4. The interlink of EGR and highly oxygenated fuels

To fully understand the scale and the advancements made by this study on lowering emission formation, Fig. 15 presents the NO_x-soot trade off, where the magnitude of the effect of introducing highly oxygenated fuels and EGR is visible. The combustion test rig allows for a key comparison of emissions with glycerol at different fuel preheating temperatures when no EGR is implemented (orange circle) to emissions with D2 fuel with also no EGR implemented (grey circle). Implementing EGR with glycerol further reduces emission formation with no apparent trade off caused by EGR (green circle)

A mayor importance is laid upon the interlinking effects of glycerol with EGR, as these allow to bypass the penalties that EGR is usually enforcing to CO and soot. This is shown in both Fig. 16 and Fig. 17, where NO_x, CO and soot were simultaneously reduced with increasing EGR. The improved trade off effect can be discerned when 0% EGR is applied and simultaneous reduction of emissions is not achievable to such extent.

A separate insight into NO_x-CO trade off is presented in Fig. 16, where yellow points present the baseline operation with glycerol and 0% EGR, whereas blue and green points represent operation with 8% and 13% EGR, respectively, all for different TIT. Based on available data throughout the literature, it would be expected that EGR would have no positive effect on CO emission formation, but the higher PAT temperatures resulting from EGR and increased heat radiation of CO_2, help with mixture preparation as the larger glycerol droplets vaporize faster. Regardless of this, the CO presence in the primary zone of CC remains high, however, since the global EQR ratio is low and oxygen is available again in the secondary and dilution zones of CC, sufficient residence time is available for notable reduction of CO. Additionally, higher PAT temperatures reduce reaction quenching and develop a more homogenous temperature profile, where less high temperature zones occur. Again, with higher PAT, higher NO_x emissions would be expected, however the dilution effect is prevailing here what results in lower NO_x emissions. This is confirmed with Fig. 16, where implementing EGR simultaneously reduces both NO_x and CO resulting in significantly reduced CO and NO_x at the same time.

Additionally, Fig. 17 presents the NO_x-soot trade off. Again it is shown that simultaneous reduction of both pollutants is possible when external EGR is introduced. Here, an important effect was observed that is proprietary to gas turbines. While three main mechanisms were identified for soot reduction already with highly oxygenated fuels without the use of EGR, these are further enhanced with incorporation of EGR. Furthermore, reactivity of soot particles is increased with EGR as discussed in section 3.3.3. Increasing the reactivity of soot is of significant importance as formation of soot particles with more reactive locations occurs in the primary zone due to dilution effect of EGR,

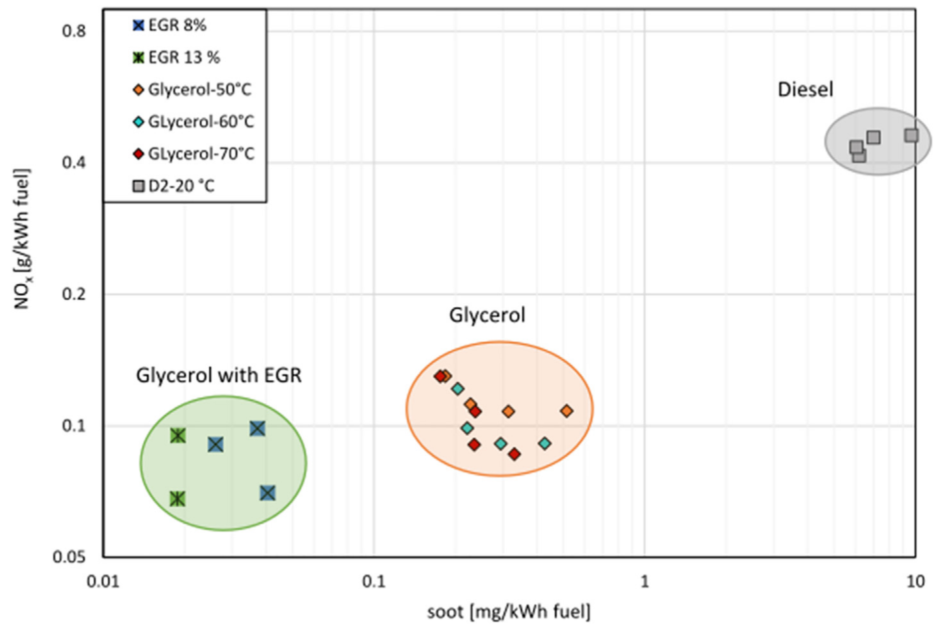

Fig. 15. NO_x soot trade off for different fuels with no different EGR ratios and fuel temperatures. Data for glycerol without EGR and D2 is taken from [6]

whereas in the secondary zone with high excess air ratio, oxygen becomes again available to react with generated soot. The process is inherently different than for example in reciprocating engines, hence transferability of improved trade-off to other combustion systems is not fully possible.

Within this observations, the approach to use highly viscous and highly oxygenated fuels that feature low cost and high availability in gas turbines with external EGR can be confirmed as fully viable and offers a significant opportunity for further development.

4. Conclusions

The study presents the first implementation of external EGR in gas turbines using highly oxygenated fuels. Obtained results demonstrate the benefits that can be achieved if existent setups with exhaust gas heat regeneration are converted to use highly viscous fuels and at the same time include moderate rates of exhaust gas share in compressor intake air. The approach presents a technically viable and cost-efficient step for significant reduction of CO, NO_x and soot emissions. The main findings obtained through close analysis of underlying combustion phenomena comprise:

- Up to three fold effective reduction in CO emissions can be achieved if 13% EGR rate is used due to increased PAT and impact of fuel bound oxygen on mixture formation.
- Reduction in NO_x is moderate, however clear benefit is observable with increasing EGR rate, ultimately reaching 20% lower values if 13% EGR is used instead of 0% EGR.
- Soot emissions are significantly reduced, reaching two-fold lower values at 13% EGR rate, confirming that when combining highly

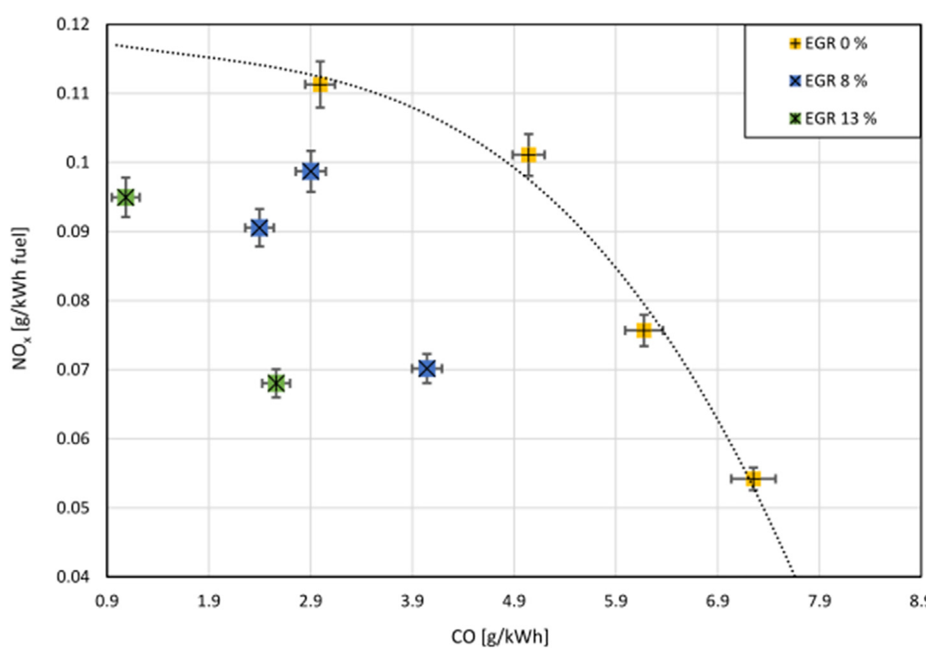

Fig. 16. NO_x and CO trade off with implementation of EGR.

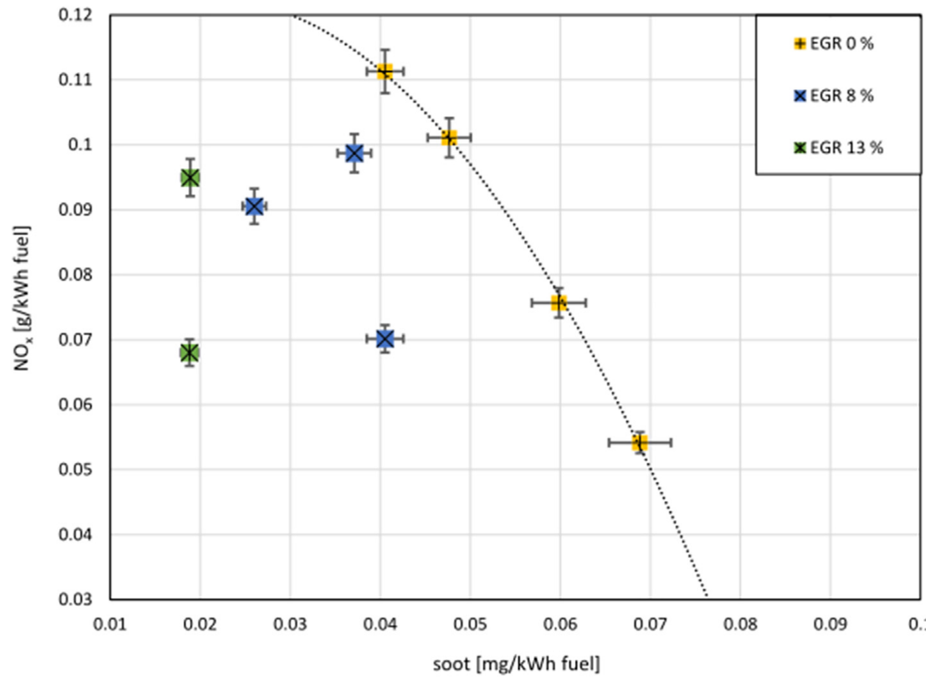

Fig. 17. NO_x and soot trade off with implementation of EGR.

oxygenated fuel and partially cooled external EGR, an order of magnitude lower soot emissions can be obtained in comparison to diesel fuel.

- The CO - NO_x trade off reveals that both pollutants can be reduced simultaneously and that highly oxygenated fuels behave differently from conventional fuels, where literature shows pronounced competing effects.
- The soot – NO_x trade off if significantly improved where both pollutants reduce simultaneously as well without increasing CO emissions. The improved trade-off is largely a consequence of increased primary air temperatures and dilution effects of EGR.

Considering practical application of proposed approach, the prerequisite for achieving aforementioned emission performance is at first implementation of required engine adaptations to accommodate highly oxygenated fuels and highly viscous fuels what was covered elsewhere [19]. When further implementing external EGR to such systems the following aspects should be taken into account:

- Although micro gas turbines with regenerative cycles offer exhaust gas temperatures between 250 °C and 300 °C, EGR rate is still limited with maximum allowable compressor intake temperature, effectively allowing EGR rates to be lower than 20%.
- To further increase EGR rates, reducing the temperature of exhaust gas is necessary, making CHP based systems highly suitable for this approach since exhaust gas outlet temperature can be between 50 °C and 100 °C.
- The power output of the system is reduced in line with temperature at compressor intake.
- The effective efficiency moderately reduces but maintains values above 25% in systems with exhaust gas heat regeneration.

Being the first experimental study in the area of highly oxygenated fuels in gas turbines employing exhaust gas heat recirculation, the presented work is providing the first confirmation of technical viability. Hence, an extensive research field is opening up to include system level analyses, evaluation of performance and estimation of potentials that reduction of emissions in this way is offering to environmental footprint of power generation sector.

CRediT authorship contribution statement

Žiga Rosec: Writing - original draft, Software, Formal analysis, Data curation. **Tomaž Katrašnik:** Writing - review & editing, Funding acquisition, Methodology. **Urban Žvar Baškovič:** Investigation, Formal analysis. **Tine Seljak:** Writing - review & editing, Conceptualization, Project administration, Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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