

Effects of high viscosity biofuels on PM and NO_x emissions of a micro gas turbine

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Introduction

The presented paper focuses on combustion analysis of a highly oxygenated and viscous fuel in an internal combustion micro gas turbine (MGT). The goal of the study is to present the benefits and challenges of utilization of such fuels in engines rather than in atmospheric combustion devices, which is currently the most common approach. To represent highly viscous and oxygenated fuel, glycerol of technical quality was used as a model substance. While technical difficulty of the proposed approach enveloping internal combustion engine and highly viscous fuel is rather high, the environmental benefits in terms of NO_x emissions and PM emissions are significant as concentrations of both species in exhaust gasses are significantly reduced. At the same time, the effective efficiency of internal combustion engines is rather high, which can further reduce the CO₂ footprint of such approach. The foreseen benefits are linked mainly to the analysis presented in the study, namely the influence of oxygen content in the fuel, which reduces the formation of NO_x due to lower nitrogen presence in the flame zone. This altered local air-fuel ratio could also suppress soot formation resulting in significantly reduced PM emissions. Besides these beneficial effects, the influence of highly oxygenated and viscous fuel is also perceivable through higher CO and THC emissions, however results indicate that increasing turbine inlet temperatures and fuel preheating temperatures could reduce also these two species without negatively affecting other pollutants. Significant benefits of the fuel in terms of environmental effects indicate that further investigation and development of this approach might provide a new alternative energy source considering the large quantities of crude glycerol currently available.

Methodology

To overcome the significant technical difficulty linked to glycerol viscosity, the reduction of it is mandatory to obtain sufficient quality of atomization, which is capable of supporting combustion process under conditions present in MGT. Considering the performance of experimental system, which was developed to test various prototypes of engine components it is foreseen that innovative solutions linked to the atomization system will allow the use of crude glycerol without blending or upgrading and only by using preheating of the fuel. Particular importance is laid upon thermal protection of the nozzle, which prevents development of carbon deposits that are a limiting factor in increasing the fuel temperatures [1]. Key data of the tested GLY is presented in Table 1, together with properties of benchmark diesel fuel according to EN590:2011 (D2). The molecular structure of GLY is presented in Fig. 1.

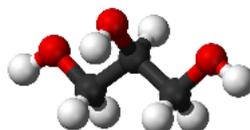


Fig. 1 Structure of glycerol molecule.

In terms of viscosity, it is currently considered that $15 \text{ mm}^2/\text{s}$ [2] is the maximum value for gas turbines, although some authors propose even lower values $12 \text{ mm}^2/\text{s}$ [3] or $10 \text{ mm}^2/\text{s}$ [4]. However these values are linked to pure pressure atomizers, which are known to have limited turndown ratio and are highly sensitive on viscosity as the energy for liquid jet break up should be delivered solely by fluid pressure. More suitable nozzles for high viscosity fuels are therefore twin-fluid atomizers which feature better turn down ratios (i.e. in certain interval of mass flows, the atomization ability is minimally influenced) and are less sensitive to viscosity as energy for liquid jet breakup is delivered also by atomizing air stream [1]. However, the viscosity levels of glycerol are too high to be accommodated even by twin-fluid nozzles.

The design of injection nozzle followed the commercially available solution, however the nozzle discharge surfaces were modified in order to accommodate the thermal protective layer. By this the radiative and convective heat transfer was reduced to a point where no fuel decomposition occurred in the internal mixing chamber of the nozzle and formation of deposits on discharge surfaces was minimized. This is a key improvement which enables high preheating temperatures which otherwise cause excessive fuel coking issues as was already reported in [1].

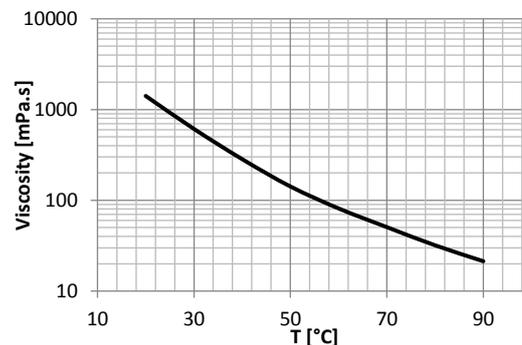


Fig. 2 Temperature dependence of GLY viscosity.

Results

Fig. 3 presents CO emissions at different turbine inlet temperatures (TIT) for both fuels and for all tested temperatures. Based on the physical and chemical characteristics of the fuels presented in Table 1 and Fig. 2, particularly the viscosity and density of GLY and to some extent also its evaporation curve, the higher CO emissions of the GLY in Fig. 3 are expected. The nearly 10-fold higher viscosity of the GLY compared to D2 impairs the atomisation ability of this fuel, resulting in a longer life span and penetration depth of the larger and denser droplets. Increased penetration depth of the droplets is the consequence of decreased surface to mass ratio of the droplets due to the larger initial droplet diameter and due to the increased density of GLY. Furthermore, delayed evaporation of droplets (which in this case feature lower surface to volume ratio due to larger diameters) and unfavorable evaporation curve of GLY in comparison to D2, requiring higher temperatures is in this case causing prolonged time interval in which the mixture preparation takes place. Furthermore, high autoignition temperature (370°C) and high boiling point (290°C) of the GLY can also play a significant role (by offsetting the ignition of the mixture leading to a shift of reactive zone towards the end of primary zone. These phenomena inevitably lead to higher CO emissions in exhaust gas stream.

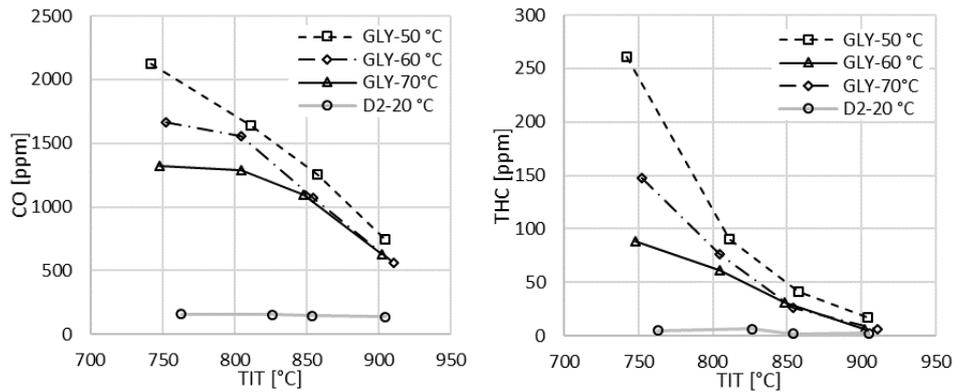


Fig 3 CO and THC emissions of D2 and GLY

Considering the upper phenomena, responsible for formation of larger quantities of CO with GLY in comparison to D2 it was presumed that increasing TIT would lead to suppression of listed phenomena by increasing the temperature levels in combustion chamber and increasing the heat transfer to the droplets and consequent evaporation rate of the fuel.

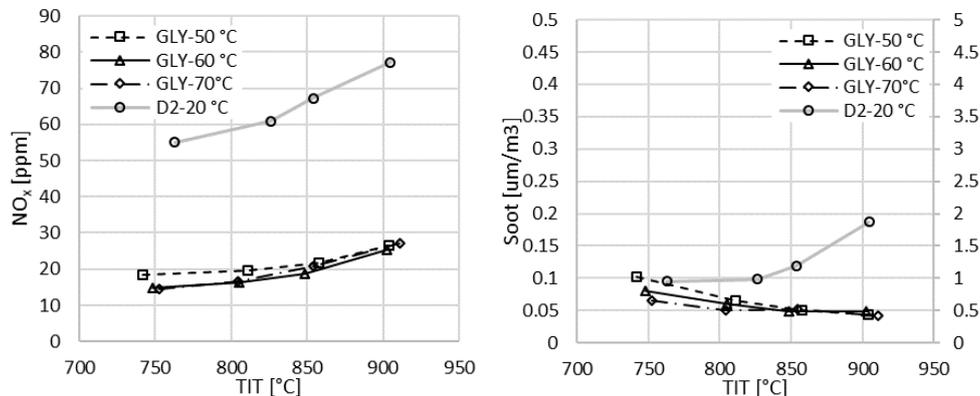


Fig 4 NO_x and PM emissions of GLY and D2.

The NO_x emissions concentrations reported in Fig. 8 demonstrate two distinctive trends. The first is linked to fuel type and the other one to TIT, which is related also to primary air temperature and EQR. The highest NO_x emissions are observed with D2 and high TIT, followed by GLY and high TIT.

Low levels of NO_x in combustion of GLY might be the consequence of high oxygen content and low stoichiometric ratio in GLY. The oxygen, contained in GLY represents as much as 35% of stoichiometric oxygen. Thus, to obtain a mixture of GLY and air inside a flammability interval, the amount of required air is smaller. Therefore, also lower amount of nitrogen is delivered into high temperature zone thus reducing the possibility for thermal NO_x formation.

The TIT dependence of soot from GLY is exhibiting the opposite trend as D2 which features for an order of magnitude higher PM emission which reduces with TIT. As the energy density of the mixture is comparable to D2 and the adiabatic flame temperature of GLY is close to that of D2, the influence of TIT on soot formation with GLY should be similar to that of D2.

The reason for these unexpected trend can be linked to high oxygen content in GLY. Bonded oxygen becomes during dissociation directly available in the flame zone in the form of free

radicals, resulting in high local C/O. As GLY contains approximately 35% of the oxygen required for its stoichiometric combustion, the C/O ratio is always below 1, even in the most rich part of the mixture, whereas for D2 this value is easily exceeded on the rich side of the diffusion flame and approaches infinity where only fuel vapor is present. Thus, areas with local EQRs below the soot formation threshold are more likely to occur with GLY. Additionally, the high O/C ratio of the fuel also leads to a much earlier onset of exothermic oxidation reactions, even when a very low quantity of air is available in the fuel-air mixture. Thus, the temperatures in the fuel rich areas could be elevated above the soot formation threshold when using GLY. Similar observations with very low soot were already made in [5], where glycerol was combusted in an atmospheric furnace and in [6,7] where high preheating temperatures of similar highly oxygenated fuel also reduced soot concentration below measurable limit.

Conclusions

This study revealed that oxygen content is the main drivers for low measured NO_x and PM concentrations. The elemental composition of GLY was reflected over the whole measurement range of the experimental system. The lowest NO_x emissions were obtained with GLY at low TIT while lowest PM emissions were obtained with GLY at high TIT.

To fully confirm the technical feasibility of crude glycerol use in gas turbines, also the influence of contaminants (catalyst residuals, mineral matter and water content) was investigated, however the results will be provided in the later stages of the study. GLY can also be considered as a model for highly oxygenated viscous biofuel. In this category, liquefied wood from solvolysis process, hydrothermal liquefaction products and biomass pyrolysis oils are the most known fuels, the findings provided in this study are therefore partially transferrable also to other oxygenated viscous biofuels.

References

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