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The impact of spray quality on the combustion of a viscous biofuel in a micro gas turbine

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HIGHLIGHTS

- Combustion of straight vegetable oil was tested in a micro gas turbine.
- The study is focused on the effect of fuel viscosity on combustion efficiency.
- A linear relation between viscosity and CO emissions was found.
- The pressure-swirl atomizer showed limited tolerance to increased viscosity.

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ABSTRACT

The relation between spray quality and combustion performance in a micro gas turbine has been studied by burning a viscous biofuel at different fuel injection conditions. Emissions from the combustion of a viscous mixture of straight vegetable oils have been compared to reference measurements with diesel No. 2.

The effect of fuel viscosity on pollutant emissions is determined by adjusting the injection temperature. The measurements confirm that a reduction in fuel viscosity improves the spray quality, resulting in faster droplet evaporation and more complete combustion. CO emission levels were observed to decrease linearly with viscosity in the tested range. For the pressure-swirl nozzle used in the tests, the upper viscosity limit is found to be 9 cP. Above this value, droplet evaporation seems to be incomplete as the exhaust gas contains a considerable amount of unburned fuel.

Additionally, the influence of increased injection pressure and combustor temperature is evaluated by varying the load. Adding more load resulted in improved combustion when burning diesel. In case of vegetable oil, however, this trend is less consistent as the decrease in CO emissions is not observed over the full load range.

The outcome of this study gives directions for the application of pyrolysis oil in gas turbines, a more advanced biofuel with high viscosity.

1. Introduction

1.1. Background

Depletion of fossil resources and concerns about the environment have led to increased attention to energy production from biofuels. Although various renewable fuels and conversion technologies have been developed to address these issues, gas turbines can play a major role in the transition to a more sustainable energy supply. Gas turbines offer some important advantages over other technologies, including high power-to-weight ratio, high reliability, high flexibility and low pollutant emissions [1]. Furthermore, the scalability of gas turbines allows for the production of heat and power in a decentralized manner. With overall energy efficiencies above 80% in cogeneration plants, this technology is considered to be promising for distributed applications [2,3].

When it comes to application of liquid biofuels, the relatively robust burning characteristics in gas turbines is of particular interest. While reciprocating engines are very sensitive to problems such as clogging and delayed ignition, gas turbines have shown good potential to cope with alternative fuels. Experimental studies have shown that most common biofuels, such as bioalcohols and biodiesel, can already be burned in pure form in standard or slightly modified combustor designs without any significant problems [4–9].

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Nevertheless, with the eye on the environment and sustainability, it is more interesting to focus on second generation biofuels derived from biomass residues. In this class of biofuels, fast pyrolysis oil is considered as a promising example [1,10–12]. Pyrolysis oil, also referred to as pyrolysis liquid or bio-oil, is produced by thermal decomposition of biomass. By quenching of the condensible vapors formed in the cracking process, a combustible liquid is obtained containing a wide variety of chemical species.

Due to the rather low feedstock quality and the random nature of the decomposition reactions, the properties of pyrolysis oil are very different from those of conventional fossil fuels. For this reason, pyrolysis oil is not directly suitable for use in combustion devices, including gas turbines. The few attempts that have been made revealed major problems as incomplete combustion, flame instability and coke formation on combustor walls [4,5,13–16]. Therefore, it is generally concluded that fuel blending or thorough modification of the gas turbine is required for successful application.

The poor combustion behavior of pyrolysis oil is partly a result of its unfavorable chemical properties. For instance, the low heating value and the presence of non-volatile matter slow down the mass and heat transfer inside a combustion chamber considerably. Researchers have been trying to improve the quality of pyrolysis oil for several decades by optimizing the production process or upgrading the raw product [10,17,18]. Unfortunately, these studies did not yet result in a feasible method for obtaining pyrolysis oil with properties similar to fossil fuels. For this reason, more research has been initiated with a focus on adapting existing combustion devices to operate on pyrolysis oil in its present form.

In the development of such fuel flexible combustion systems, it is of crucial importance to look into the influence of fuel properties on the spray quality. The atomization process governs the evaporation and distribution of fuel inside the combustion chamber and is therefore closely related to the combustion performance [19]. In case of pyrolysis oil, most of the conventional atomization techniques tend to deliver a fuel spray of poor quality. This issue is mainly attributed to the high viscosity of the oil, which has a dampening effect on the fuel breakup mechanism [20,21]. Since the time required for complete evaporation is considerably higher when the fuel is poorly atomized, some fraction of the fuel may impinge on the liner. The increased evaporation time can be a major cause for the aforementioned problems that were encountered in pyrolysis oil burning tests.

Aside from the effect on the evaporation process, atomization also has a significant influence on the combustion kinetics of pyrolysis oil. Due to the chemical instability of this biofuel, polymerization reactions at elevated temperatures lead to the formation of non-volatile matter inside the droplets during their flight in the combustor [15,22–25]. Research on individual droplets has revealed that these undesired reactions are suppressed in case the droplet heating rate is very high [26,27]. As the heating rate is highly dependent on droplet size, small droplets are required to avoid deterioration of the pyrolysis oil quality during evaporation. Hence, given the current properties of raw pyrolysis oil, improved atomization can be seen as a key factor towards efficient combustion.

Due to the adverse effect of high viscosity on spray quality, viscous fuels are normally preheated to a temperature at which the flow properties are acceptable. However, in case of pyrolysis oil, the allowable preheating temperature is limited to around 80 °C because of the chemical instability as explained above. This limitation implies that the viscosity of pure pyrolysis oil cannot be lowered to a level that is typical for distillate fuel oils. As a consequence, the spray quality might be affected even if the oil is preheated, so that the technical feasibility of burning pure pyrolysis oil in existing gas turbines should be questioned irrespective of the combustion kinetics.

1.2. Aim of the study

In this work, the effect of viscosity on the combustion efficiency in a micro gas turbine is investigated by changing the injection temperature of a viscous fuel. Here, the fuel viscosity at the pressure-swirl nozzle is used as measure for the spray quality, while CO emissions indicate the combustion efficiency. The main goal is to determine the sensitivity of the combustion process to an increase in fuel viscosity and to identify a typical maximum viscosity for which the atomization is still acceptable.

Straight vegetable oil has been used as the fuel for the experimental test campaign. This biofuel is selected to capture the effect of viscosity, while excluding the complex chemistry effects associated with pyrolysis oil. The stability of vegetable oil allows for preheating up to high temperatures, such that a wide range of viscosities can be tested. The experiments with vegetable oil have been compared to reference measurements with diesel. Next to viscosity effects, also the influence of load has been examined. The results from this study can be useful in formulating practical guidelines for good atomization of pyrolysis oil as a first and very important requirement.

1.3. Previous work

Literature on the combustion of straight vegetable oil in gas turbines is scarce; only few works have been found that are similar or closely related to the present study. Habib et al. [28] tested several vegetable oil-based biodiesels (soy, canola and recycled rapeseed), an animal-derived biofuel and their 50% blends with Jet A fuel in an unmodified 30 kW gas turbine. Engine performance and emissions are reported for all biofuels except for the pure animal fat biofuel due to its high sooting potential. However, no information is given about the injection system and fuel injection temperature.

Cavarzere et al. [29] investigated the performance of a Solar T-62T-32 micro gas turbine fed by blends of diesel and straight vegetable oils in different concentrations. The researchers were able to gradually increase the vegetable oil content up to 100% without running into any particular problems. Unfortunately, the authors did not report the injection temperatures used during the test runs, while they mention that the fuel tanks for vegetable oil blends were heated to reduce the viscosity.

Significant work was published by Chiaramonti et al. [30], who performed experiments with diesel, biodiesel and vegetable oil in a Garrett GTP 30-67 micro gas turbine equipped with a pressure-swirl atomizer. It was found that the combustion of pure vegetable oil and its blends with diesel required preheating of the fuel to at least 120 °C. At idle conditions, combustion could not be sustained even at this temperature. However, the results generally showed that preheating the fuels reduced CO emissions. The effect of fuel temperature was measured to be more pronounced at partial load. Also, it is concluded that the combustion efficiency for vegetable oil at 120 °C is very similar to that of diesel at standard conditions.

These conclusions are confirmed by field tests with a slightly modified Capstone C30 conducted by Prussi et al. [31]. In this micro gas turbine, straight vegetable oil was injected by air-assist atomizers at three different temperatures. CO emissions decreased with higher preheating temperatures, especially at low load conditions, and were nearly the same as for diesel in case of maximum load. Considering the strong influence on the engine performance, viscosity was identified as the most important parameter to be controlled. Comparison of the data obtained by Prussi et al. with other studies will only be possible to a limited extent, however, because the fuel temperatures are not reported explicitly.

The experimental work discussed above indicates that the research on this topic is in an early stage. Straight vegetable oil has been applied in gas turbines only few times, with varying