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Characterization of viscous biofuel sprays using digital imaging in the near field region

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HIGHLIGHTS

- Biodiesel, vegetable oil and glycerin sprays have been studied using PDIA.
- The study is focused on the effect of fuel viscosity on the spray characteristics.
- Viscosity has a strong effect on the breakup length in pressure-swirl atomization.
- The results are compared to combustion experiments with a micro gas turbine.
- The penetration depth of ligaments can be a critical factor in burning viscous fuel.

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ABSTRACT

The atomization of biodiesel, vegetable oil and glycerin has been studied in an atmospheric spray rig by using digital imaging (PDIA). Images of the spray were captured in the near field, just 18 mm downstream of the atomizer, and processed to automatically determine the size of both ligaments and droplets. The effect of the spray structure in this region is of major interest for the combustion of biofuels in gas turbines. The sprays were produced by a pressure-swirl atomizer that originates from the multifuel micro gas turbine (MMGT) setup. Various injection conditions have been tested to investigate the influence of viscosity on the spray characteristics and to assess the overall performance of the atomizer. The spray measurements have been compared to combustion experiments with biodiesel and vegetable oil in the micro gas turbine at similar injection conditions. The results show that the primary breakup process rapidly deteriorates when the viscosity is increased. A higher viscosity increases the breakup length, which becomes visible at the measurement location in the form of ligaments. This effect leads to an unacceptable spray quality once the viscosity slightly exceeds the typical range for conventional gas turbine fuels. The SMD in the investigated spray region was not significantly affected by viscosity, but mainly influenced by injection pressure. The data furthermore indicate an increase in SMD with surface tension. It was found that the penetration depth of ligaments can have major impact on the combustion process, and that the droplet size is not always the critical factor responsible for efficient combustion. The measured delay in primary breakup at increased viscosity shows that pressure-swirl atomization is unsuitable for the application of pure pyrolysis oil in an unmodified gas turbine engine.

1. Introduction

To increase the share of renewables and to reduce CO_2 emissions in future power generation, a considerable amount of research has been conducted on fuels derived from biomass sources. One of the biofuels developed in the last few decades is pyrolysis oil, also known as bio-oil, biocrude or pyrolysis liquid. Pyrolysis oil can be produced from a variety of forest and agricultural biomass waste materials [1] via thermochemical decomposition in absence of oxygen. The dark brown, combustible liquid that results from this process with a yield of 65–75 wt.% is considered as a promising alternative for fossil fuels in industrial applications. However, the presence of a large amount of oxygenated compounds gives pyrolysis oil markedly different properties compared to conventional petroleum-derived fuels. The difference in fuel properties has led to a number of technical hurdles that need to be addressed before application in combustion devices can be successful on the long term.

An interesting possibility is the use of pyrolysis oil in gas turbine engines. Gas turbines are relatively fuel-flexible and are capable of generating power on both large and small scales, suiting the

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demands of the future energy system. Pyrolysis oil combustion in gas turbines has therefore been subject of a few experimental studies in the past years [2–8]. These studies, conducted in both scientific and industrial test rigs, have shown that the use of pure pyrolysis oil often leads to major problems. Reported issues include high CO emissions, flame instability, fuel deposits in the hot section and unburned particles in the exhaust gas.

The poor burning characteristics of pyrolysis oil are related to its low volatility, low heating value and limited stability, but can also be attributed to the fuel spray quality. Pyrolysis oil has a high viscosity with respect to the conventional fuels, which causes the atomization process to be less effective [9]. Preheating the oil in order to reduce the viscosity to an acceptable level is only allowed to a limited extent, because certain reactive compounds tend to polymerize at elevated temperatures. Whereas the atomization of pyrolysis oil can be problematic for this reason, it is essential to deliver very fine sprays to cope with the adverse combustion properties of this biofuel. Improving the atomization is not only required to restrict the evaporation time, but can also largely prevent the formation of carbon-rich particles which are sometimes seen as sparks during combustion tests. Previous studies have shown that the amount of solid residue after evaporation decreases with the drop size, since polymerization reactions are suppressed at high heating rates [10,11].

For these reasons, it is important to measure and compare the quality of sprays under different conditions. Information on the influence of fuel properties helps to further define biofuel specifications and atomization requirements for combustion applications. Spray measurements are furthermore essential for understanding some of the phenomena that occur during test campaigns with various viscous biofuels, i.e. to separate the effects of spray charactistics from those of chemical kinetics.

The literature concerning the atomization of pyrolysis oil or other viscous fuels for gas turbine applications is scarce. Only few studies on this topic have been found, which consider a variety of atomizers, liquids, test conditions and sample locations. Detailed information on the spray in the near field region is not often reported in these studies, presumably due to measurement difficulties. However, the spray characteristics close to the atomizer are of special interest for evaporation and mixing, and besides most relevant as input data for spray combustion models in CFD.

Krumdieck and Daily [12] were among the first researchers to study the atomization of pyrolysis oil. They tested internally and externally mixed air-assist atomizers for use in spray combustion experiments with this biofuel. The authors concluded that the internally mixed atomizer performed much better, but did not describe the spray quality in terms of droplet size.

López Juste and Salvá Monfort [2] studied the general appearance of a pyrolysis oil spray produced by a pressure-swirl atomizer in preparation for combustion tests. To obtain a viscosity below 10 cP, the pyrolysis oil was preheated to 115 °C. They found that the spray angle decreased from the standard value of 60° for diesel to only 20° for pyrolysis oil. The cause of this remarkable change was not identified. Since the researchers wanted to avoid any major modifications to their injection system, the combustion tests were carried out using a mixture of pyrolysis oil and ethanol to lower the viscosity. Figures defining the spray quality were not discussed.

Significant work on pyrolysis oil atomization has been done by Garcìa-Pèrez et al. [13]. Their study includes drop size measurements in sprays of pyrolysis oil (at 80 °C), No. 2 diesel (at 25 and 40 °C) and water (at 25, 60 and 80 °C). The sprays were produced by two different Delavan pressure-swirl atomizers (type A and W) at varying injection pressures. Droplet sizes between 2 and 197 μm were measured 50 mm downstream of the atomizer using Malvern Mastersizer equipment, which is based on laser diffraction technology. Within the tested range of injection pressures, the Sauter mean diameter (SMD) of the pyrolysis oil sprays was 45–75 μm for atomizer type A, and 35–70 μm for atomizer type W. These values were typically 10–20 μm higher than those measured in the diesel and water sprays. The difference was attributed to the relatively high viscosity of the pyrolysis oil, which was still 17 cP despite preheating to 80 °C.

Atomization studies related to other viscous biofuels than pyrolysis oil can provide useful insights as well. Crayford et al. [14] investigated the pressure-swirl atomization of a bio-oil derived from the food industry. Details about the viscosity of the bio-oil are not given, but a temperature of 27.5 °C was indicated as the melting point. The researchers used phase Doppler anemometry (PDA) to record the droplet size and velocity simultaneously at a specified point, while backlight photography was employed for providing information on the general spray structure. The global SMD of the full cone bio-oil spray, derived from local measurements at 6 axial and 9 radial positions, decreased from 59 to 55 μm when preheating the fuel from 60 to 80 °C. At 80 °C, the global SMD and structure of the bio-oil spray and the benchmark gas-oil spray were similar. However, the authors underline that characterization of an entire spray using a single drop diameter is problematic. Close to the atomizer, 25 mm downstream, a preheat temperature of only 70 °C would be necessary to match the SMD measured in the gas-oil case.

Panchasara and Agrawal [15] examined straight vegetable oil (VO) sprays produced by an airblast atomizer at different oil temperatures and air-to-liquid ratios (ALR). Laser sheet visualization was used to capture spray images for qualitative analysis. Quantitative, pointwise measurements of droplet diameters and gas phase velocities in the full cone were performed with a phase Doppler particle analyzer (PDPA) system. It was found that an increase in oil temperature and ALR both improve the atomization, especially in the outer region of the spray. However, with a maximum SMD of only 60 μm for a VO viscosity of 28 cP, good atomization was achieved even at low oil temperature and low ALR. In the near field, 20 mm downstream, the SMDs were below 42 μm at all conditions.

Recently, interesting results have been presented on the atomization of viscous fuels using a novel method referred to as 'flow-blurring' [16–18]. In this concept, air penetrates the fuel flow in a region close to the orifice to create a turbulent two-phase mixture. The air bubbles contained in the fuel rapidly expand when exiting the nozzle, thereby disintegrating the liquid structure. This technique has been shown to deliver superior atomization performance compared to conventional airblast atomization methods and is suggested to have an advantage over effervescent atomization regarding the flow stability inside the atomizer. Droplet size measurements using PDPA in reacting glycerol sprays and in non-reacting vegetable oil and diesel sprays produced by a flow-blurring atomizer have been reported by Simmons and Agrawal [18,19]. Without preheating the liquids, they obtained SMDs of typically 25–40 μm in the glycerol spray (100 mm downstream) and 35–55 μm in the near field of the vegetable oil spray (20 mm downstream). Such SMDs are exceptionally low, considering the viscosities of respectively 930 and 50 cP. The flow-blurring atomizer is still in the research phase and not (commonly) used in practical combustion applications yet.

In this work, the effect of viscosity on spray quality has been assessed by using an economically attractive high-resolution particle imaging technique (PDIA). Sprays of three different liquids were visualized at varying injection conditions in the region near the atomizer to investigate the primary atomization process. The size of the droplets captured on the images was then determined via automated analysis. Also the effect of ligaments in the proximity of the atomizer was taken into account, showing the significance