CHALLENGES AND SOLUTIONS FOR UTILIZATION OF BIOLIQUIDS IN MICROTURBINES

Tine Seljak
University of Ljubljana, Faculty of mechanical engineering
Aškerčeva cesta 6, SI-1000 Ljubljana, Slovenia
tine.seljak@fs.uni-lj.si

Klemen Pavalec
University of Ljubljana, Faculty of mechanical engineering
Aškerčeva cesta 6, SI-1000 Ljubljana, Slovenia
klemen.pavalec@gmail.com

Marco Buffi
University of Florence, Industrial Engineering Department
Via di S. Marta, 3, 50139 Firenze, Italy
marco.buffi@re-cord.org

Agustin Valera-Medina
Cardiff University City, Gas Turbine Research Centre
Queens Buildings, The Parade, CF234aa Cardiff
valeramedinaA1@cardiff.ac.uk

David Chiaramonti
University of Florence, Industrial Engineering Department
Via di S. Marta, 3, 50139 Firenze, Italy
david.chiaramonti@unifi.it

Tomaž Katrašnik
University of Ljubljana, Faculty of mechanical engineering
Aškerčeva cesta 6, SI-1000 Ljubljana, Slovenia
tomaz.katrasnik@fs.uni-lj.si

1Corresponding author
ABSTRACT

Increased public concerns and stricter regulatory frameworks promote the role of bioliquids (liquid fuel for energy purposes other than for transport, including electricity and heating and cooling, produced from biomass). This is a driving force for development and employment of micro-gas-turbines (MGTs) due to their ability to combust bioliquids with less favorable properties in a decentralized manner. Gas turbines are characterized by relatively high combustion efficiency at relatively low concentrations of harmful emissions, relatively high effective efficiency and durability when utilizing a common portfolio of gas turbine approved fuels. It is thus desired to preserve these advantages of gas turbines also while burning bioliquids and further relying on their scalability that is crucial to efficient support of decentralized energy production at small scales. To support these objectives, MGT technology needs to allow for utilization of bioliquids with much wider spectrum of physical and chemical properties compared to common commercially available MGTs in a single MGT based plant. In this view, the present study is providing the first thorough overview of challenges and solutions encountered by researchers across the wide area of bioliquids in MGTs.
INTRODUCTION

Turbine engines have reached high level of maturity and can be considered almost irreplaceable in applications where high power to weight ratio is required. Applications range from aircraft propulsion systems to stationary power generation, however mostly in the range of high power outputs. A subgroup of gas turbines that share similar thermodynamic principle of operation with their larger counterparts are micro gas turbines (MGTs). The specific definitions of MGTs vary along the literature and are mostly constrained by power output intervals from few ten to few hundred kW (30-400kW [1], 30-330 kW [2], 25-500 kW [3], 15-300 kW [4], 30-100 kW [5], 10-200 kW [5], <1 MW [6], <300 kW [7]). These definitions are generally based on market-available MGT setups and their available range. However, irrespective of these minor definition related deviations, the following can be considered typical for MGTs:

- Single stage compression / expansion
- Uncooled turbine blades
- Low pressure ratios (up to 4)
- Low turbine inlet temperatures (below 1000 °C)
- Exhaust heat regeneration (in modern MGT)
- High volume series production with installation site independent design.

Typical state of the art MGT topology with key characteristics is presented in Figure 1. Initially, MGTs were used as field generators, aircraft start carts, auxiliary power units and rarely automotive power plants. Only recently with overall increased energy consumption, higher electricity prices and shift towards decentralized power generation made MGTs attractive also for efficient dedicated stationary power generation. In line with relative novelty of the technology, the sales are currently significantly lower than for their main competitors - reciprocating engines.

Figure 1: Microturbine topology with indicated key characteristics (adopted after [1]).
While reciprocating engines are in terms of availability, price and technology maturity indeed superior to MGTs, one of the most profound advantages of MGTs over reciprocating engines is their continuous combustion principle. In general this should allow for the use of fuels with less refined properties than reciprocating engines.

By reducing the dependence on fossil fuels and reducing the quantities of landfilled wastes, the share of bioliquids for power generation with less favorable properties is expected to increase in the future. In terms of economic attractiveness, it is often favorable to produce fuels of lower quality as their input feedstock limitations are looser and production technology is cheaper, leading to a sound business case. This offset in investment can easily be justified by exploiting slightly costlier technology (MGTs) to provide on-site power generation with high efficiency thus boosting the increased electricity share over the heat production. Within this scenario, the MGTs might become an important technology to support waste management facilities and bio refineries to achieve decentralization of energy production with bioliquids. These will in the future become less suitable for reciprocating engines. Due to the nature of MGT operation, the study is dedicated to liquid fuels as they provide higher flexibility of operation in terms of fuel production as there is no need to couple the fuel production process with energy generation (i.e. transportation is less demanding and storage is simpler). At the same time, parasitic load of gas booster used when operating MGT with gaseous fuels can account for up to 10% of total power output in case low calorific value gaseous fuels are used and capabilities of MGT are best exploited with liquid fuels. Lastly, the technical challenges linked to liquid fuels in terms of fuel atomization and mixture formation in MGT call for a dedicated study as the subject is complex and demanding.

The research efforts in the direction of combustion of bioliquids in MGTs are notable; however, the research topics are relatively dispersed and highly focused on different fuels and MGTs. The results are therefore difficult to critically assess due to the lack of an organized overview and clear guidelines for MGT design and adaptations, which is slowing the process of maturation of technology. With the aim to provide basis for further development of MGT technology for wide range of bioliquids, this paper first provides a comprehensive status overview of research on bioliquids suitable for MGTs and their production processes and secondly, it comprehensively reviews available MGT technologies and solutions for utilization of bioliquids. Finally, based on the author’s original work, several proposals for innovative solutions, guidelines and technical advances are given that allow for efficient, stable and durable operation of the MGTs for a series of bioliquids for power generation with less favorable properties compared to the ones most frequently encountered in MGTs.

The present study is thus aiming to integrate and upgrade the current knowledge through holistic interrelation in the area of bioliquids and related MGTs by:
Providing a first selective review of bioliquids and bioliquid production processes, currently proved to be suitable for use in MGTs.

Providing a first comprehensive review of current approaches towards use of bioliquids in MGTs.

Proposing a series of innovative solutions and technical advances for utilization of bioliquids with highly unfavorable properties, which extends the applicability of MGTs to wider spectra of current and future bioliquids.

BIOFUELS LEGISLATIVE FRAMEWORK

To position biofuels in terms of their future perspective and to properly assess commitment of gas turbine and MGT manufacturers, a recap of legislative actions in EU, USA and Japan is given as these are the market leading manufacturers and exporters of MGT technology.

EU legislation promoted the use of biofuels in member states by means of Renewable Energy Directive (RED – Directive 2009/28/EC, [8]) and the Fuel Quality Directive (FQD – Directive 2009/30/EC, [9]). The RED sets 10 % target as the ratio of renewable energy in road transport sector: aviation biofuels could therefore count towards the target, as well as hydrogen or electricity used in road transport [10,11]. The FQD requires that all fuel suppliers must meet the 6 % reducing target of GHG emissions by 2020 across all fuel categories provided to the market (except aviation). This is designed to be consistent with the 10 percent use of biofuels and will tend to move demand toward sustainable biofuels with higher GHG savings.

Biofuel market, whether imported or produced within the EU, must meet the Sustainability Criteria [12–14] of emission reductions targets. These criteria are under update, in particular as regards ILUC (Indirect Land Use Change) factor. Currently, a new legislation is under development [15].

As regards the US situation, there are currently two major carbon fuel policies which define sustainability issues and actions of biofuels [16]: RFS2 program (Renewable Fuel Standard) and the California Low Carbon Fuel Standard (CA-LCFS). RFS2 is a national policy that requires a certain volume of renewable fuel to replace or reduce the quantity of petroleum-based transportation fuel, heating oil or jet fuel. The RFS2 sets significant production targets of cellulosic biofuels [17]. CA-LCF has the goal of reducing the carbon intensity (CI) of the transportation fuel pool by 10% by 2020. Other efforts are underway to establish other regional low carbon fuel standards in Northeast and Mid-Atlantic States, Midwestern states.

Similarly, the Government of Japan (GOJ) introduced in 2010 a plan to introduce 500 million liters (crude oil equivalent) of biofuels by 2017, and obligated the oil industry to meet this goal [18]. In 2017, Japan confirmed its preliminary biofuel policy from 2018 to 2022, focusing on first and second generation ethanol and bio-jet fuel. Apart from the upper frameworks in different parts of the world, the large-scale production of biofuels and bioliquids is closely related to
environmental issues and legislative frameworks. Under this roof, each country has developed its national long-term strategy, which introduces defined volumes of bio-derived fuel in the global fossil fuel demand. First-generation biofuels were widespread in the past, but the competition with agriculture limited their use in favor of lignocellulosic biomass (i.e. second-generation biomass sources). Despite the conversion costs which are generally higher than for first generation biofuels (e.g. biodiesel and bioethanol), they do not compete with food crops and their feedstock availability is increasingly favored by recent legislative frameworks. Biofuels and biocrudes production pathways have costs twice or even higher to the respective quantities of fossil fuels, but crude oil price has already proven to be the main factor affecting their final costs as well as market attractiveness.

MICROTURBINE FUELS AND FUEL PRODUCTION PROCESSES

Gas turbines were historically developed to be fed with fossil-derived fuels or natural gas [19]. Depending on their function, several technologies were developed [20] and each application has its requirement in terms of fuel [21]. In aviation, for example, only fully compatible fuels, miscible with the current conventional jet fuels are tolerated [22], which can be used without any modifications in the existing aviation engines and infrastructure [23].

However, in the energy sector, technology can be adapted to the properties of fuel as long as a sufficient thermal power at the gas turbine inlet is provided. This allows a major fuel flexibility by introducing the use of a wide range of bioliquids. Gupta et al [24] published a comprehensive overview about the use of biofuels/bioliquids for gas turbine applications, focusing on fuel properties and their effect in gas turbine combustion. Due to their oxygenated nature, biofuels require defined blending walls as regards the fuel mixtures with fossil fuels (e.g. biodiesel and bioethanol when used in commercial applications), or specific dedicated technologies (in the case of bioliquids and bio-intermediates as fuel). In general, conventional biofuels are produced from cereal crops (e.g. wheat, maize), oil crops (e.g. rape, soy, sunflower, palm oil) and sugar crops (e.g. sugar beet, sugar cane) using established and commercial technology. This category includes bioethanol and biodiesel, which represent the most diffuse blending components for fossil transport fuels [25]. Production energy demand is roughly 49.8 MJ per kg of ethanol from lignocellulosic biomass [26] and 49.8 MJ kg\(^{-1}\) for ethanol from sugarcane [26].

Biodiesel comes from the transesterification process of triglycerides and due to its chemical compatibility it can be blended into fossil diesel fuel. Biodiesel can be easily used in MGTs without significant modification for its properties close to diesel fuel [4]. However, the main role of bioethanol and biodiesel is set to transport fuel sector for the EU Renewable Energy Directive [9], to cover the use of food based biofuels at 7 percent (in volume) by 2020. Production costs in terms of energy is roughly 15-20 MJ per kg of biodiesel from sunflower oil [27].
Biogas derives from anaerobic digestion of biodegradable materials such as agricultural waste, and it is mainly composed by CH\textsubscript{4} and CO\textsubscript{2}. A comprehensive review of biogas production and benefits, as well as its role as alternative fuel for gas turbine, was carried out by Jahangirian and Engeda [28]. The direct use in combustion devices is most profoundly related to the presence of impurities in the gas, which greatly influence the durability of materials used in MGTs. Biogas upgrading before the use in commercial applications becomes a fundamental issue [29] and meeting the criteria set for impurities content is challenging [30]. The energy demand for production is relatively low in the range 4-10 MJ per kg of biogas from anaerobic digestion of agriculture residue [31].

Advanced biofuels derive from recent technologies aimed to convert in biofuels the non-conventional lignocellulosic or aquatic biomass such as energy crops, algae, agricultural residues (e.g. straw, corn stover), forestry resources and waste streams (e.g. UCO, food wastes). The most adopted pathways (already commercial) include bioethanol production via enzymatic conversion of lignocellulosic feedstock, and hydrotreating of lipids (HEFA, Hydrotreated Esters and Fatty Acids). While bioethanol from lignocellulosic material consists in the same biofuel as bioethanol from sugars, the biofuel produced by hydrotreatment of lipids consists in a higher quality product than biodiesel (i.e. a drop-in fuel, a fully compatible fuel for blending with traditional hydrocarbon fuels). The main product from triglycerides hydrotreatment is often called “green” or “renewable” diesel, that consists of a mixture of paraffinic hydrocarbons in the range of diesel fuel [32]. HEFA process includes the production of HRJ (Hydrotreated Renewable Jet fuel), already used in commercial flights as drop-in fuel. The use of HRJ as fuel for APU- or small scale gas turbine was largely studied in literature [22,33–35], with no significant modifications to commercial technologies. The sustainability of advanced biofuels is strictly related to net GHG reduction across each "value chain" (the specific combination of sustainable feedstock, conversion process and final products), with no "negative effect" on biodiversity or land use.

Advanced technologies include also pyrolysis, liquefaction or solvolysis of lignocellulosic material, where the main products are liquid viscous bio-derivatives. In fast pyrolysis process, biomass decomposes very quickly in an inert atmosphere to generate mostly vapors and aerosols, charcoal and non-condensable gas. Subsequently, a dark brown homogenous mobile liquid is condensed (FPBO, Fast Pyrolysis Bio-Oil). In direct liquefaction processes, the products are often denoted as Liquefied wood (LW). The direct use of this bio-intermediate liquids as fuel represents a promising opportunity to store and convert energy in CHP units. However, a large amount of oxygenated components is present into FPBO as well as the other bio-intermediates from hydrothermal processes and direct liquefaction processes, thus they have a polar nature and cannot be mixed with hydrocarbons. As investigated by Van De Beld et al [36] for reciprocating engines and Czernik and Bridgewater [37] for gas turbines, the direct use of fast
pyrolysis oil as fuel requires major modifications in several parts of the systems, from fuel storage to nozzle. A comprehensive overview about fast pyrolysis oil properties is given by Chiaramonti et al [38], which highlighted that large part of engine components has to be properly selected in order to operate with a viscous, acidic liquid. In terms of production costs, the production of FPBO should be convenient if integrated in a large plant where also pyrolysis co-products are economically enhanced. The typical energy requirement for production accounts for roughly half of the products LHV [39]. For solvolysis process, this value is lower, in the range below 10 % of LHV [40].

The emissions of production processes of biofuels and bioliquids are generally linked to the primary source of energy required for production, whereas waste material flows (i.e. char from pyrolysis process, glycerol from biodiesel production and digestate from ethanol production) and their impact on emissions can only be assessed through LCA studies which are out of the scope of the paper.

APPLICATIONS OF BIOLIQUIDS IN MGT

Experimental combustion research of bioliquids in MGTs can roughly be divided in three levels of complexity when considering the type of MGT:

- Commercial, state of the art setup,
- Setups derived from APUs and small jet engines,
- Dedicated test rigs, usually based on automotive turbochargers.

The most widespread commercial MGT systems in the recent years were Capstone C30 [41] and Turbec T100 [42], which are both state of the art, high efficiency, dedicated CHP units. Both are equipped with exhaust gas heat regeneration to obtain higher efficiencies (26% and 31% respectively). APU derived MGTs are usually simple-cycle operated without heat regeneration, thus having far lower efficiencies which at can at low loads drop below 10%, but they give valuable information on performance of wide spectra of fuels used in MGT combustors as they are relatively easy available and thus attractive for several research teams. Dedicated test rigs are mainly built with the idea that they are able to reproduce conditions present in commercial MGT. Although they do not in detail mimic the MGT combustion process, they allow for significant diversity of testing parameters. In this view, the contribution they can offer to identification of interrelated phenomena and sensitivity of combustion process to a wide variety of different operating parameters is of significant importance. Moreover, their modular design enables testing of separate components, materials and control strategies which gives far more information about the behavior of bioliquids than studies that are performed in relatively non flexible commercial systems.

In line with technical possibilities, studies in commercial, state of the art turbines are currently limited to straight vegetable oils (SVO) and their blends with diesel (D2) or biodiesel
(BD) from various feedstock. Thus 15% and 30% SVO-D2 blends were investigated for 500h [43] and pure SVO for 250h [44], revealing higher NO\textsubscript{x} emissions and deposit formation in a premixing chamber. The deposits mostly consisted of phosphorus. CO emissions were on a similar level as with D2. Similarly, blends of kerosene, rapeseed oil and sunflower oil were investigated at 10 % and 20 % at two different load conditions [45], showing that no global behavior differences can be observed on MGT except for PM emissions, which are higher with SVO-D2 blends. Furthermore, blends of BD from soy oil and D2 showed higher emissions of CO and NO\textsubscript{x} and required modifications of fuel injector to manage with mentioned exhaust gas species [46]. 50 % BD mixture with D2 and kerosene were also investigated at full and half load with emphasis on the particulate emissions. These showed a dual peak at 2-3nm and 20-30nm. Several studies were performed also purely on virtual level what was in some cases a prerequisite for performed experimental work. Thus 0-D and CFD analyses of combustion chambers were performed in several studies either with the aim to analyze the atomization, mixing and combustion process [47], [48], [49], [50], [51], [52], [53], however most of the research was oriented towards gaseous biofuels which are out of the scope of this paper.

The broadest research of bioliquids in MGT was performed in commercial systems, which were not primarily designed for high efficiency stationary and decentralized power generation rather being mostly derived from APU units, small jet engines or field gensets for military use. These are:

- Garrett GTP 30-67 [54] [55]
- DG4M-1 [56] [57]
- Solar T-62T-32[58]
- Allison gas turbine - D424A [59]
- T63-A-700 Allison[33]
- Teledyne RGT-3600 [60]
- J69-T-29 [61]
- Armfield CM4 [62]
- Artouste MK113 APU[34]
- Model jet engine, Sr-30 [63]

Listed studies addressed wide spectra of vegetable oils, waste greases and biodiesels blended in different blending ratios with D2 or kerosene. The employed approach usually consisted of start-up with conventional fuel followed by switching to a tested bioliquid. Some studies also incorporated preheating to reduce the viscosity of the bioliquid [56,58,59,63]. Considering more demanding bioliquids with significantly unfavorable properties, few studies investigated blends of biomass pyrolysis oil with JP4 or D2 [57,61,64] and JP4/char slurries [61]. Blends of pyrolysis oil and ethanol were also investigated in a small scale (30kW) combustor

[64]. The general findings consist of elevated CO, HC, NOx, and smoke number with increasing pyrolysis oil content. The CO and HC emissions reduced with increasing load. Preheating of the mixtures to 40-50°C was mandatory and the results were supported by preliminary investigation of material analyses after contact with tested bioliquids, which revealed relatively little influence of pyrolysis oil on materials during limited time intervals.

Even more demanding bioliquids were tested in dedicated turbocharger based experimental MGT setups. Here, the most comprehensive work was performed with different formulations of liquefied lignocellulosic biomass [65–67], tire pyrolysis oil [68] and D2. The approach used was a variation of turbine inlet temperature, primary air temperature, different fuel preheating temperatures as well as analyses of materials in contact with the fuel and combustion products [69]. By mapping the majority of the design space of experimental setup, guidelines for development/adaptation of commercial setups were given. This approach also allows the implementation of an efficient workflow, where holistic assessment of fuel to MGT relation is possible within a limited set of experiments [69] and at far lower costs. The most important advantage is the possibility to investigate the dependency of the MGT response on an isolated parameter as the control system and also topology of the experimental MGT is fully flexible.

Current research of bioliquids in MGTs is therefore almost exclusively oriented towards lighter biomass derived bioliquids (SVO, BD) and only three research groups investigated highly viscous bioliquids with significantly unfavorable properties [57,61,64,65] which are the most attractive due to their price advantage and wide spectra of feedstock that can be used to produce them.

**TECHNICAL ADVANCES ENABLING THE USE OF ALTERNATIVE BIOLIQUIDS IN MGT: SUMMARY AND OUTLOOK**

Previous sections comprised an overview of available studies across the community in the area of utilization of bioliquids in MGTs. This forms a basis for independent analysis of innovative solutions and technical advances for utilization of bioliquids with highly unfavorable properties. Here two distinctive approaches are available:

- Upgrading of MGT components to adapt to properties of the analyzed fuels and maintaining the original fuel formulation in order to preserve the economic viability.
- Optimization of the investigated fuel by blending or upgrading to suit the fuel properties to MGT requirements if upgrading of MGT components turns out to be insufficient.

When using state of the art commercial setups, often the second approach is more attractive due to relatively non flexible design of available MGTs rendering upgrades challenging. Thus, blending of tested fuels with D2 or kerosene is employed. However, if it is
possible to upgrade the MGT, the first approach with implementation of upgrades to different components of MGT is often more viable, as it allows for preserving low production costs of original fuel resulting in enhanced market viability. In this case, boundaries of the appropriate design space are generally explored in dedicated experimental setups, which tend to push the limits of acceptable interval of fuel properties and enable investigation of wide spectra of bioliquids.

In several cases, where bioliquid properties are especially challenging for a given MGT, the combination of both approaches turns out to be the most successful. Thus in several studies, blending of fuels was combined with moderate preheating of the fuel. This is also the main approach when using state of the art commercial setup, whereas adaptations beyond this step are rarely employed with few exceptions of injection nozzle adaptations. Based on the existent knowledge and the outcome of current studies, it is possible to interrelate the available results and provide recommendations for utilization of existing bioliquids in MGTs. Furthermore, based on original author’s work, advances that are required to design future-proof MGT systems are provided through guidelines on MGT adaptations required for efficient utilization of fuels with less favorable properties compared to the ones encountered in current MGTs. These guidelines will be proposed by addressing separate MGT components by means of their impacts on the overall operation of the MGT. This interrelation of general objectives on Efficiency, Low emission operation and Durability/Reliability and proposed upgrading measures of selected components is depicted in Figure 2.
Fuel system

Fuel properties that in general impose challenges when designing the fuel delivery system are: density, viscosity, heating value and fuel composition as well as its pH value [70]. First three parameters are considered when designing the fuel supply system, whereas the last two can significantly impact its durability. As various bioliquids feature very wide spectra of fuel compositions and their properties, a holistic assessment of all listed fuel properties needs to be considered early in the development phase of the system to ensure future proof designs of MGTs for wide spectra of bioliquids. This predominantly comprises:

- **Selection of appropriate materials** being a key for long-term operation of fuel system and crucial for mitigating the intake of contaminants from corrosion products to the fuel delivery line. This selection can be optimized with dedicated immersion test either under stationary or moving flow conditions. Different planned preheating temperatures can be tested and further analysis can be performed by investigating the SEM images of surfaces and cross sections of immersed material [70].

- **Appropriate design of a fuel flow path** which is a key for efficient preconditioning of the fuels with increased viscosity. This can simultaneously mitigate the deposition rate of fuel degradation products and coke formation on heating surfaces. Therefore, specific designs of process lines, which are tailored to the degradation properties of fuels, are required. Fuel aging and chemical stability at elevated temperatures, point of thermal decomposition and fuel evaporation curve need to be assessed in these analyses. These data should be used to carefully plan the layout of the preheating process in order to avoid substantial stationary points in the fuel lines and heating surface temperatures. Inappropriate design, which can result also in formation of gaseous phase during preheating might cause also safety issues. This can be omitted by pressurizing the system above the boiling point of the most volatile fuel component at the hottest point of fuel system. Inline heating devices with low surface temperatures work best as they minimize the residence time of the fuel on high temperatures, however they are not always the best choice due to possible significant pressure drop or high heating surface temperatures.

At this point, detailed analyses of molecular composition of the fuel are generally unnecessary unless the corrosion and deposition forming phenomena require development of tailored materials to withstand the required preheating temperatures. Although the preheating temperature is primarily limited with fuel properties, which could, for the fuels with high temperature stability, allow significant preheating, the temperature should be kept as low as possible from emission point of view in order to avoid formation of carbon deposits on the injection nozzle as discussed below. By following these guidelines, it is possible to successfully
utilize bioliquids with viscosities above 1 Pa·s at room temperature, which is two orders of magnitude higher than currently accepted limits (15 mm²/s [19], 12 mm²/s [24], 10 mm²/s [38]).

Importance of selection of materials with appropriate corrosion resistance is shown in Figure 3, where increasing contaminant content in the fuel along the fuel lifecycle is presented. It is shown that increasing content of stainless steel corrosion products originates from the preheating of bioliquid with low pH value. Vertical axis shows content of elements in solid residue after TGA. The data is obtained through original author’s research and emphasizes that corrosion-borne fuel contaminants might play an important role also in the durability of hot path components as listed species (Fe, Ni, Zn, Cr) could play a major role in formation of abrasive combustion products.

**Injection system**

Considering the wide interval of expected bioliquid viscosities, several different atomization nozzles based on either pressure or air-assist atomization can be used to accommodate different bioliquids. Majority of existent studies used original nozzles, hence blending and preheating of the fuels was used to suit the nozzle viscosity and surface tension requirements. When more challenging bioliquids are to be used, the startup and shut-down procedure of MGT is usually done with lighter fuels to prevent starting problems and allow for proper cool-down procedure. In this case, it is of significant importance that the following constraints are taken into account:
Maximizing nozzle turn down ratio is crucial to ensure efficient atomization performance of the nozzle for different start-up/shut-down fuels and part load performance. Application of pure pressure atomization is therefore disadvantageous as fuel flows strongly influence the atomization process [71]. Air-assist atomization is the preferred method to maintain relatively similar droplet size for wide spectra of the fuel flow. They employ large flow cross-sections and are generally designed for fuels with high viscosities [72] (up to 120 mPa·s [73]) as the energy, required for spray break-is delivered via momentum of atomizing air. If it is not possible to utilize air-assist nozzle, LHV and density of start-up/shut-down fuel should be adjusted to suit the bioliquid in use.

Thermal protection: Considering the reduced thermal stability of several bioliquids, the nozzle adaptations at high preheating temperatures are oriented towards reduction of heat transfer from primary zone of the combustion chamber to the nozzle surfaces. Although air-assist atomizers naturally reduce heat transfer by providing a boundary layer of cool air on the nozzle discharge surfaces, their protection is still insufficient. Nevertheless, thermal breakdown of the fuel and consequent coke formation on nozzle exit orifice is still influenced by:

- fuel decomposition temperature,
- viscosity and consequent preheating temperature,
- oxygen content in the fuel,
- primary air temperature in combustion chamber.

For future bioliquids with high viscosity, low temperature stability and possibly high oxygen content, thermal protection is of utmost importance as these bioliquids tend to be prone to significant carbon residue formation impairing fuel atomization and increasing exhaust...
emissions. This is often a consequence of their complex molecular composition. An example of internal-mixing thermally protected nozzle is given in Figure 4. Note the layer of insulating ceramic material.

**Combustion chamber**

Besides injection system, combustion chamber design can be considered as one of the most important enablers for utilization of alternative fuels. State of the art MGT systems often employ the use of partial premixing of the fuel-air mixture, which most often requires fuels with very little or no evaporation residue. In future bioliquids it will not be always possible to comply with this specification as already vegetable oil exhibits proneness to deposit formation and causes phosphorous deposits on the premixing tube [43]. Staged combustion and pre-vaporization principles are therefore mostly applicable to the conditions where surface impingement of the fuel droplets is not present. In case that solid residue after evaporation of the fuel is present, simple single stage combustion chamber might be applicable at the expense of emission concentrations. In this case, depending on the fuel density, evaporation rate, viscosity, surface tension and evaporation residue, the following measures might alleviate the fuel deposition rate on the walls of combustion chamber and improve the emission response of MGT:

- **Increasing the volume of combustion chamber** results in longer residence time of the spray [74], enabling the evaporation of the fuel before wall impingement. However, this measure has also a negative impact, as it significantly reduces the primary zone velocity and momentum thus disrupting the appropriate flow pattern. Potential absence of primary zone recirculation might cause severe deposit formation or excessive CO, PM and NO\textsubscript{x} formation. This negative impact of larger volume can be offset by again increasing the velocities through increased primary air temperature as discussed below.

- **Increasing primary air temperature** promotes fuel evaporation rate by increasing heat transfer to the droplets. It also increases velocities and thus compensates for the increased volume of the combustion chamber being favorable for reducing fuel deposition on the combustion chamber walls. High primary air temperature is thus one of the main enablers for attaining successful combustion of highly viscous bioliquids [70]. The drawback of high primary air temperature might result in fuel nozzle deposit formation, as radiation of high temperature primary zone gasses provides up to 90% of heat transfer to the fuel nozzle [19] and thus deposit formation is highly likely with preheated fuels. Therefore, this measure frequently needs to be combined with the application of thermal protection of the nozzle being addressed in the previous section. In terms of technical complexity of this adaptation, the state of the art commercial MGTs are proved to be an ideal starting point due to their
high primary air temperature [70], however the adaptation of the fuel nozzle is required in most cases. In addition, increase in primary air temperature is generally attained through exhaust gas heat regeneration, which further boosts efficiency of the MGT.

Listed approaches lead to greatly improved operational stability when using highly viscous bioliquids. The stability of operation can be assessed through time-resolved measurements of thermodynamic and emission parameters, namely combustion chamber pressure and CO, THC emissions and NOx emissions. An example of variation of key MGT parameters before/after introducing exhaust gas heat regeneration is given in Figure 5 (adopted from study with liquefied wood [70]), which clearly shows the increased variability of parameters if low primary air temperature (i.e. simple cycle operation) is used. The most profoundly influenced parameters are CO, THC emissions and combustion chamber pressure, which deviates according to energy balance due to fuel deposition on combustion chamber walls. The negative effect of this approach is the increase of NOx emissions, which increase with increasing primary air temperature (in case of regenerative cycle operation) due to higher temperature levels in the primary zone of combustion chamber and increased EQR ratio and thus oxygen availability.

Control strategies

Beside improvements on the component level of the MGT and the overall system layout, effective and tailored control strategy is also very important for efficient MGT operation. Generally, studies dealing with high viscosity bioliquids revealed that high primary air temperatures and high turbine inlet temperatures aid in reduction of CO emissions [59,66], whereas for the lighter bioliquids the trend is less pronounced as influence of EQR ratio prevails in the latter case [68]. Increased aldehyde emission from hydro treated FAE (Fatty acid ethyl esters) and GTL (Gas to liquid) bioliquids at low load operation are also reported [34]. This indicates that selection of appropriate control strategy is depending on the properties of tested fuels. Considering these limitations, the proposed control strategies are the following:

- **Operation at full load or near full load** to avoid lower turbine inlet and primary air temperatures negatively impact the availability of sufficient activation energy for onset of combustion reactions. Additionally, augmented velocity profile in primary zone due to lower velocities leads to impaired mixture formation, further reducing the possibility to fully oxidize THC and CO. At lower power outputs, the operation could be further limited by reduced atomization performance due to lower fuel mass flow through the nozzle [56].

- **Slower rate of load following** to avoid possible blow-off due to higher sensitivity of bioliquids on air-to-fuel ratio and sensitivity to flow conditions in primary zone.
Figure 5: The impact of exhaust gas heat regeneration on stability of operational parameters in MGT, fired with highly viscous bioliquid (upper-w/o regeneration, lower w/ regeneration) [70].
Listed strategies can be loosely or more strictly imposed during MGT operation, depending on the phenomena that are responsible for these limitations. These can be condensed into the following:

- Impaired atomization quality at low fuel flows reduces the possibility for low load operation due to sensitivity of nozzles on varying fuel flow. In case of lighter bioliquids and air-assist atomization, this constraint is less relevant [56,70,74], however with highly viscous bioliquids with low evaporating rate it becomes more limiting as they require sufficient pressures to maintain atomization quality.

- Temperature levels in combustion chamber during low load operation prevent successful mixture formation and lead to deposit formation [65,66] as well as aldehyde formation [34]. Formation of deposits is most prominent at viscous bioliquids with complex molecular composition and high autoignition temperature. Sufficiently high temperatures also aid at reduction of droplets residence time and faster mixture formation thus requiring higher loads.

- Load following is reduced due to higher sensitivity of some of the bioliquids on air-to-fuel ratio and sensitivity to flow conditions in primary zone. This is mainly applicable to oxygenated fuels with high volatile content or narrower flammability limits which can cause blow-out due to lean flame extinction.

**Fuel flexibility**

Significant variability of physical and chemical properties among different bioliquids is suggesting that required technical complexity of different MGT components and subsystem might vary greatly when targeting different bioliquids. The universal solution for utilization of wide variety of bioliquids would therefore be challenging to develop, however the widest applicability would be obtained with technically the most advanced MGTs, developed for highly viscous fuel (using fuel preheating system, high temperatures of primary air, significantly improved fuel nozzles and appropriate control strategy in terms of power output constraints). The fuel-tolerance of such system would be relatively high as was proven in several studies listed above, where dual-fuel or even triple-fuel MGTs were developed, capable of using several different bioliquids (from biodiesel blends to highly viscous fuels with low calorific value [57,61,68]). However, under such conditions, fuels with favorable physical and chemical properties are usually used as start-up and shut-down fuels and although the MGTs are capable of using them continuously, they rarely do so as the cost advantage is most often the biggest with low grade fuels. As such systems are linked with high development and production costs, the use of MGTs with very large fuel flexibility is most often suboptimal, albeit it is possible. Thus, tailoring of available commercial MGTs with advanced design for target bioliquid by
incorporating minimum required adaptations is the most efficient in terms of cost to performance trade-off. This approach can also provide the most attractive business case as adaptations are tailored for targeted fuel. Exceptions are possible if high fuel flexibility is specifically required due to very large variability of fuel input. An example of significantly increased fuel flexibility in experimental MGT [70] reveals that wide variety of different fuels can be used in the same MGT setup. The two outmost cases of extent of adaptations is presented in Table 1. Generally, the highly upgraded MGT, intended for use of LW (highly viscous fuel) on the right is also able to support operation with tire pyrolysis oil (TPO). To some extent, bioliquids with properties in between TPO and LW can also be used, however dedicated testing is mandatory to confirm the applicability of solutions to other bioliquids.

Table 1: Extent of adaptations and applicable range of fuel properties for an experimental setup developed in [70].

<table>
<thead>
<tr>
<th>Property</th>
<th>Liquefied wood</th>
<th>Tire pyrolysis oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/dm³)</td>
<td>1.3</td>
<td>0.923</td>
</tr>
<tr>
<td>LHV (lower heating value) (MJ/kg)</td>
<td>20.2</td>
<td>41.0</td>
</tr>
<tr>
<td>Stoichiometric ratio</td>
<td>6.8</td>
<td>~13.8</td>
</tr>
<tr>
<td>Viscosity (mm²/s at 80°C)</td>
<td>106</td>
<td>3.94</td>
</tr>
<tr>
<td>VHV (volumetric heating value)</td>
<td>26.26</td>
<td>37.84</td>
</tr>
</tbody>
</table>

**Minimum requirements of the system**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Liquefied wood</th>
<th>Tire pyrolysis oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel system</td>
<td>Conventional</td>
<td></td>
</tr>
<tr>
<td>Injection system</td>
<td>Air-assisted</td>
<td>Pressure-swirl</td>
</tr>
<tr>
<td>Nozzle thermal protection</td>
<td>Required</td>
<td>Not necessary</td>
</tr>
<tr>
<td>Startup/shutdown</td>
<td>Dual fuel system (startup/shutdown with diesel fuel)</td>
<td>Single fuel system</td>
</tr>
<tr>
<td>Primary air temperature</td>
<td>Operation in regenerative cycle</td>
<td>Operation in simple cycle</td>
</tr>
</tbody>
</table>

**Possible Operational parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Liquefied wood</th>
<th>Tire pyrolysis oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel temperature</td>
<td>100°C</td>
<td>20°C</td>
</tr>
<tr>
<td>Turbine inlet temperature</td>
<td>750, 800 and 850°C</td>
<td>750, 800 and 850°C</td>
</tr>
<tr>
<td>Primary air temperature</td>
<td>450, 480 and 506 °C</td>
<td>182, 175 and 170°C</td>
</tr>
</tbody>
</table>
CONCLUSIONS

By providing a first thorough overview of existent knowledge in the field of bioliquids and their applicability to MGTs, mapping of state of the art solutions used among several research teams was performed. These served as a basis to provide the most important guidelines for further research and utilization of bioliquids. With the current research efforts present across the industry and academia, bioliquids from different processes could become viable energy carriers, supporting decentralized waste management facilities with the aim for energy recovery of various feedstock and reduction of landfilled waste as well as recovery of valuable materials with near to zero external energy consumption.

ACKNOWLEDGMENT

The work was financially supported by the Slovenian Research Agency through program P2-0401 and project L2-5468.
REFERENCES


