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Experimental Analysis of a Micro Gas Turbine Fuelled with Vegetable Oils from Energy Crops

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Abstract

This paper deals with the technical feasibility of the use of straight vegetable oil (SVO) as gas turbine fuels.
First, this paper reports the results of the experimental characterization of different vegetable oils, derived from energy crops, and of blends of diesel and vegetable oil in different concentrations (from pure diesel to pure vegetable oil). The considered vegetable oils were obtained from different types of oilseeds (rapeseed, sunflower, soybean) and were cultivated under different agronomic scenarios. The SVO properties determined experimentally are SVO elemental composition, lower heating value, density, specific heat and viscosity, for which this paper provides a practical overview, coming both from experiments and literature data.
Secondly, the paper experimentally evaluates the behavior of a Solar T-62T-32 micro gas turbine fed by vegetable oils. The vegetable oils are supplied to the micro gas turbine as blends of diesel and straight vegetable oils in different concentrations, up to pure vegetable oil. The paper describes the test rig used for the experimental activity and reports some experimental results, which highlight the effects of the different fuels on micro gas turbine performance and pollutant emissions.

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"Keywords: Gas Turbine; Vegetable Oil; Experimental Analysis"

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Nomenclature

c	specific heat
C	compressor
CC	combustion chamber
CO	carbon monoxide
EGT	Exhaust Gas Temperature
HHV	Higher Heating Value
LHV	Lower Heating Value
N	rotational speed
NOx	nitrogen oxide
p	pressure
P	power
Q	volume flow rate
RH	relative humidity
T	temperature
T	turbine
v	valve
x	SVO fraction in SVO/diesel blend
ν	kinematic viscosity
ρ	density

Subscripts and Superscripts

amb	ambient
c	compressor
co	cut-off
f	fuel
i	inlet
o	outlet
el	electric

Acronyms

ICRPE	Internal Combustion Reciprocating Piston Engine
MGT	Micro Gas Turbine
SVO	Straight Vegetable Oil

1. Introduction

In recent years, the global energy market has been influenced by the sharp increase in oil price, the concern about global warming caused by greenhouse gas emissions and the reduction of fossil fuels supply. For these reasons, there is an increased interest in the use of renewable sources, which is testified by Europe 2020 agenda which aims to reduce greenhouse gas emissions by 20 % compared to 1990, increase energy efficiency by 20 % and cover at least 20 % of energy needs by means of renewable sources [1].

Among the renewable sources, biomass is very important because of the considerable benefits of its use, in terms of environment, socio-economic concern and technology. In fact, since biomass derived fuels are predictable, the energy systems based on these types of fuels do not represent a critical issue for the transmission and distribution grid. In addition, the use of biomass can reduce greenhouse gas emissions and also encourages economic development and employment in rural areas. A further advantage of the use of biomass is the possibility to use various technologies that allow both small-scale production, according to the spirit of decentralization and medium scale plants.

Emilia-Romagna is one of the Italian regions with the highest production of energy from biomass, i.e. 13.3 % of Emilia-Romagna energy demand [2]. In this context, a research project named “Biomass for energy production” has been developed to evaluate technical solutions for the enhancement of the agricultural resources of the territory of Ferrara, thanks to products with high added value, such as renewable fuels for electric and thermal energy production.

Renewable fuels (also called bio-fuels) can be gaseous (biogas and syngas) or liquid (biodiesel or straight vegetable oil) [3]. Although the most successful use of liquid biofuels has been proven in the transport sector (this priority is also confirmed by [4]), recently there has also been a growing interest in the industrial sector. A potential market for this type of fuels is related to micro gas turbines (MGTs), which are becoming more popular due to characteristics such as small size, fuel flexibility, low maintenance costs and low emissions.

With regard to liquid biofuels, vegetable oils can be either used as raw products (SVO - straight vegetable oil) or transformed into biodiesel by means of the transesterification process. In many experimental applications, refined vegetable oils, oil-diesel blends, biodiesel and diesel-biodiesel blends are used, while SVO is not frequently used and, therefore, research and experimentation are still required. Moreover, most of the studies are related to Internal Combustion Reciprocating Piston Engines (ICRPEs) [5-7]. Therefore, there is still a lack of technical literature and field experience on MGTs fed by straight vegetable oil. In fact, the only experiences on MGTs fed by vegetable oil are mainly related to biodiesel [8-13]. The number of experimental tests on MGTs fed by SVO is even more scarce [9,14,15]. Some experiments were also conducted by using SVO/diesel emulsions [16]. A thorough review on the use of alternative fuels for gas turbine feeding in the aviation sector was conducted by Blakey et al. in [17], where a summary of the recent alternative fuel flight test campaigns is presented. This paper documents some tests performed by using hydrogenated vegetable oil, while it shows that the use of SVOs is still very limited.

Therefore, the potential of feeding an MGT by means of SVO is still to be exploited, as also highlighted in [14]. The main advantages of the use of SVO is that SVO (i) can be easily produced on-farm in decentralized mills (i.e. close to the decentralized power plant and, as a consequence, with the lowest costs of production and transportation) and (ii) is characterized by a high greenhouse gas reduction effect [14,18]. Instead, the main technical issues are that (i) the injection system can be considerably deteriorated by SVO (since it is usually much more viscous than standard diesel [19]) and (ii) the control system should be redesigned to account for the lower LHV of SVO.

This paper reports the results obtained in the framework of the above mentioned research project “Biomass for energy production”. In particular, experimental crops of rapeseed, sunflower and soybean were cultivated and SVOs were obtained from their seeds by means of mechanical extraction. These biofuels were first experimentally characterized [19] and then used to fed a Solar T-62T-32 micro gas turbine, in order to experimentally evaluate its behavior [20]. The vegetable oils were supplied to the micro gas turbine as blends of diesel and straight vegetable oils in different concentrations, up to pure vegetable oil.

The paper provides a practical overview, coming both from experiments and literature data, on the properties of SVO and of blends of diesel and vegetable oil in different concentrations (from pure diesel to pure vegetable oil), such as elemental composition, lower heating value, density, specific heat and viscosity.

Moreover, the paper describes the test rig used for the experimental activity on the Solar T-62T-32 micro gas turbine and reports some experimental results, which highlight the effects of the different fuels on MGT performance and pollutant emissions.

2. Energy crop chain

The agricultural experimentation covers twelve hectares (approximately 30 acres) of agricultural land cultivated with rapeseed, sunflower and soybean. In addition to producing the raw material to obtain vegetable oils, the agricultural experimentation was designed to assess: i) the possible differences among the oils obtained from different varieties of the same plant species grown on soils with different structural characteristics (e.g. medium texture or clayey soil), with particular interest for seed and oil yield; ii) the economic viability of the production of crops specifically grown for biofuel production, compared to traditional crops.

The considered species for vegetable oil production are rapeseed, sunflower and soybean, which are the most common for energy purposes. In particular, where temperate climate allows two crops per year, the soybean is well suited to be grown as the second crop after rapeseed, to maximize the profitability. Moreover, soybean fixes nitrogen in the soil.

Oil has to be extracted from the plant cells, which are surrounded by a protein matrix. Nowadays the extraction techniques are mechanical (usually by means of pressing) or chemical (by means of solvents, usually hexane). The mechanical extraction is carried out on seeds containing more than 20 % of fat (rapeseed and sunflower), while the chemical extraction method is recommended for lower values of fat content. The products of the process are (i) crude oil and an expeller cake, if the extraction is mechanical, or (ii) flour, in the case of chemical extraction.

The crude oil obtained from the extraction can be adjusted by using physical and chemical treatments in order to correct the pH and eliminate impurities (proteins, gums, resins, etc.) and pigments (bleaching). To obtain a refined oil, two processes can be used: (i) purification, which includes the removal of water, suspended impurities and mucilage (gums), and (ii) refining, which aims to obtain the degree of quality required by the considered food or industrial application.

According to the Italian legislation in force when the research project “Biomass for energy production” was developed [21], only straight vegetable oil obtained by means of mechanical extraction (pressing) can receive incentives for energy production from biomass. For this reason, the vegetable oils considered in this paper were all obtained from oil seeds by using mechanical pressing. Figure 1 shows seed and oil yields obtained from the fields, where the scatter (see the bars in Fig. 1) can be attributed to the different seeds, different type of soil and agronomic path. The values are in good accordance with literature data [22,23]. In fact, seed yields depend more significantly on the type of crop (an average of 3.29 t/ha for rapeseed, 3.64 t/ha for sunflower and 2.76 t/ha for soybeans), as well as the type of cultivation. Oil yields of rapeseed and sunflower are higher (on average, 1.15 t/ha and 1.07 t/ha, respectively), while the soybean oil yield (on average, 0.24 t/ha) is lower compared to the other two crops. The low value of the soybean oil yield can also be attributed to the fact that the seeds were planted as the second crop after rapeseed harvesting.

The SVO to be used in the MGT was obtained by means of seed pressing, decantation, centrifugation and filtration. Since the vegetable oils were not chemically refined, they may contain substances that, under certain conditions of pressure and temperature, produce polymerization within the MGT injection system. To avoid clogging up the fuel system, the SVOs have been blended with diesel, in increasing mass fractions, as documented in [20].

3. SVO experimental characterization

The specific characteristics of vegetable oils depend on the type of oilseed [23]. For this reason, a specific chemical and physical characterization of the oils is requested. In general, the oil composition in terms of carbon, hydrogen, oxygen and nitrogen percentage varies depending on the agricultural species and agronomic path [22, 24, 25]. However, it was noted that the type of seed slightly influences the SVO elemental composition. Compared to diesel, all the analyzed SVOs presented a lower amount of carbon.

The higher (HHV) and lower (LHV) heating value of vegetable oils is lower than that of diesel by 9 – 14 %. In fact, while diesel can be assumed to have an LHV equal to 43 MJ/kg [26], the LHV of vegetable oils usually ranges between 37 MJ/kg and 39 MJ/kg, according to literature data [22,27-29]. From the experimental results reported in Tab. 1, it can be seen that the LHV of rapeseed is 37.21 MJ/kg and that it is only slightly higher than that of sunflower and also of soybean (in fact, all SVOs have an LHV of approximately 37 MJ/kg). However, different indications can be found in literature, as for instance paper [23], which states that sunflower LHV is always higher than rapeseed and soybean LHV.

The specific heat was also evaluated experimentally, for different temperature values, in an appropriate range for possible SVO heating. The specific heat of rapeseed was always higher than that of sunflower and also of soybean.

Since the SVO density is usually higher than diesel density (which is in the range 810 – 870 kg/m^3 at 20 °C, according to [26,30,31]), SVOs have a greater inertia, which affects the fuel jet penetration of the combustion chamber. As shown in Fig. 2, the difference among the density values of the three oils is absolutely negligible. This is also confirmed by considering the blends of rapeseed and soybean at 60 % diesel. The reduction of the density of the blend is equal to approximately 6 %, regardless of the type of oil.

Straight vegetable oils are extremely viscous: the average viscosity value is about ten times higher than diesel at the same temperature [31,33], though viscosity depends on the type of SVO. The high viscosity implies modification in the behavior of the engine: in fact, it increases the maximum injection pressure, causing a delay due to a lower start-up, a lower vaporization rate and an inefficient mixing with air in the combustion chamber [34-36].

For these reasons, a reduction of engine performance and durability occurs when ICRPEs designed to work with diesel are fed with vegetable oils. The high viscosity of vegetable oils also significantly affects emissions. In fact, vegetable oil-diesel blends produce slightly higher emissions than diesel, because of the poor atomization. The viscosity can be reduced by heating the oil before injection or heating filters, ducts and tanks [34, 36, 37]. Since the viscosity is the main technical challenge for the use of SVOs, this quantity is analyzed both for pure SVOs and for SVO/diesel blends. The interest for vegetable oil blends comes from the fact that blends are characterized by a viscosity value closer to diesel than to vegetable oil (i.e. the increase of the viscosity of the blend is less than proportional with respect to the increase of the SVO content), so that blends can be used in a gas turbine combustion chamber with minor modifications.

Tab. 1. Experimental HHV, LHV, specific heat at 20 °C and density at 20 °C.

	HHV [MJ/kg]	**LHV [MJ/kg]**	***c*** **[kJ/(kg K)]**	**ρ [kg/m^3]**
Rapeseed	39.70	37.21	1.95	916.5
Sunflower (Barolo)	39.59	37.17	1.90	918.2
Sunflower (Olekko)	39.53	37.07	-	918.5
Soybean	39.44	36.98	1.87	920.1
Diesel [26]	-	43	1.85	837

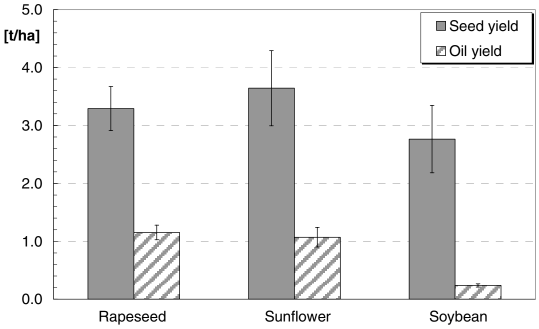

Fig. 1. Experimental seed and oil yields.

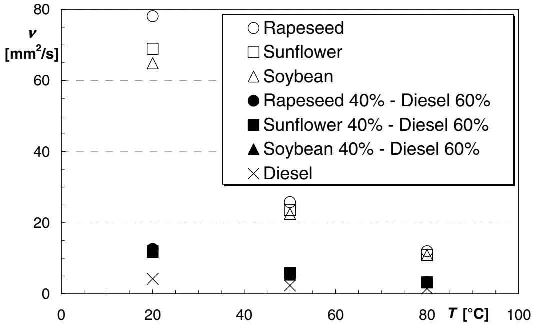

Fig. 3. Experimental kinematic viscosity for the three SVOs and blends with diesel (40 % SVO and 60 % diesel).

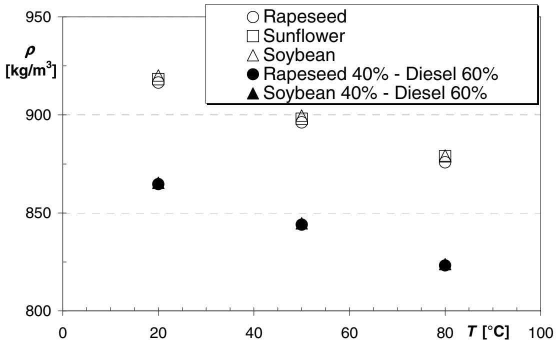

Fig. 2. Experimental density for the three SVOs and rapeseed and soybean blends at 60 % diesel.

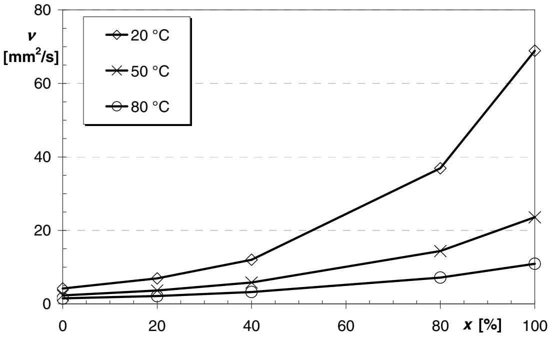

Fig. 4. Experimental kinematic viscosity for sunflower oil blends, for three temperature values.

Figure 3 reports the results for the kinematic viscosity: while the values for pure SVO are slightly different, the kinematic viscosity of blends of the three representative samples and diesel, by considering blends at 40 % of SVO (rapeseed, sunflower or soybean) and 60 % diesel, are very close to each other. The results can be explained by combining two effects: (i) use of an SVO/diesel blend instead of pure SVO and (ii) effect of SVO density to pass from dynamic to kinematic viscosity. These values are in accordance with the literature data [22, 28, 33, 36, 38].

The effect of different sunflower blends is reported in Fig. 4, which provides a rule to decrease SVO viscosity, by acting either on SVO temperature or SVO/diesel blend (or by combining the two effects). For instance, it can be observed that it is possible to keep SVO kinematic viscosity lower than 10 mm^2/s even with pure sunflower SVO when the sunflower SVO is heated at 80 °C (which is considerably lower than sunflower flash point temperature). Otherwise, if an SVO is heated at 50 °C, like in practical applications, an SVO kinematic viscosity lower than 10 mm^2/s is granted only for blends with no more than 60 % of sunflower SVO.

4. Micro gas turbine test rig

The test rig, of which the layout is shown in Fig. 5, consists of a micro gas turbine Solar T-62T-32, which, coupled with an alternator and an integrated three phase inverter, can supply 50 kVA at full load.

The MGT fuel feeding system is composed of three tanks, one for diesel and two for vegetable oils, which are heated and thermally insulated. This system is provided with a heating control system realized by two thermostats, one per each heated tank. Since the heaters must operate in immersion, it was necessary to introduce a control, that switches off the heater power supply and cuts off the fuel heating when the minimum fuel blend level is reached.

The fully instrumented MGT is shown in Fig. 6 and a brief description of the sensors is provided in the following.

The sensor (pickup) used to determine crankshaft speed rotation is a variable reluctance sensor originally part of the MGT. This device is coupled with a tachometer which displays the instantaneous speed and converts the frequency signal obtained by means of a pickup at 0–10 V continuous voltage, which is directly acquired by the acquisition system. The conversion from frequency to the voltage signal is characterized by an accuracy of 0.1 % on the voltage reading.

The volume fuel flow sensor Q_f is a volumetric oscillating disk sensor, with a measurement accuracy of 1.0 % of the reading and full scale of 420 l/h. It was placed downstream the fuel tank and therefore after the fuel boost pump, in order to measure the actual MGT fuel consumption.

The two fuel gauge pressure transducers were respectively placed at the outlet section of the high pressure fuel pump and right before the rail that feeds the MGT injectors. The last one allows the evaluation of the injection fuel pressure within the combustion chamber. This is fundamental to evaluate pressure losses between the fuel pump and the injectors. The evaluation of the ignition fuel pressure allows, if necessary, the resizing of the injection nozzles.

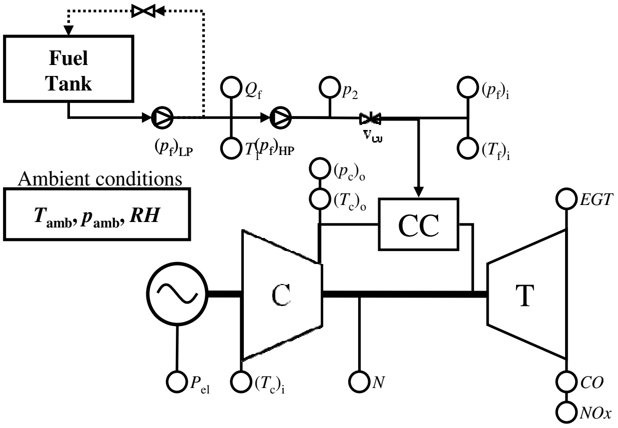

Fig. 5. MGT test rig and sensors.

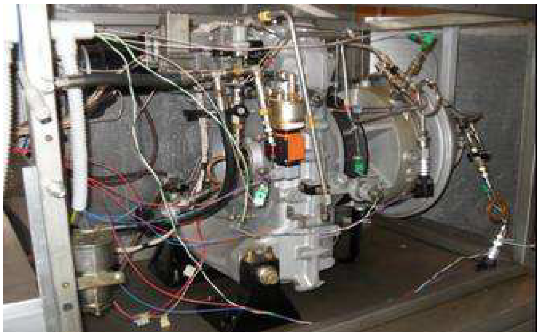

Fig. 6. View of MGT and sensors.

These transducers are characterized by a thick film ceramic pressure element: the full scale is 100 barg and the accuracy is 0.5 % F.S.. The compressor discharge pressure transducer is also characterized by a thick film ceramic pressure element with full scale of 6 barg and accuracy of 0.5 % F.S..

The most significant temperature measurements are measured by means of K-type thermocouples. The temperature values are corrected by means of a correction curve obtained by comparing the measured value to a reference measurement chain (which has an uncertainty of ± 0.5 °C), inserted into a calibration furnace, characterized by a temperature uniformity of ± 0.05 °C.

Finally, the measuring system also includes an emission analyzer, characterized by one catalytical and four electrochemical transducers. The emission analyzer allows the measurement of: carbon monoxide CO and nitrogen oxides NOx (sum of NO and NO_2) with accuracy of 4 %, oxygen O_2 with accuracy of 5.0 % and unburned hydrocarbons C_XH_Y with accuracy of 1.0 % (all accuracy values at F.S.).

Signal acquisition was realized by using a compact data acquisition (NI cDAQ) equipped by National Instruments and by developing a logging program with NI LabView software. This logging program allows the current values of acquired parameters to be displayed on PC screen, in order to manage data report parameters and the configuration of the thermo-hygrometer, barometer and emission analyzer.

5. Experimental tests at idle condition with SVO feeding

In order to analyze the performance of an MGT fuelled by SVO (pure or blended with diesel), the first step is the experimental characterization when the MGT is powered by using diesel only, in order to identify a baseline condition. The results of the characterization with diesel feeding are reported in [20].

After the experimental determination of the MGT operation powered by diesel, some tests were carried out by using blends of vegetable oil and diesel, from 5 % to 100 % of SVO. All the tests were performed by imposing the opening of the fuel flow valve, so that, when the MGT is fed by diesel, the shaft rotates at nominal speed. This same opening was maintained in all tests, with the exception of 100 % SVO feeding, since the self-sustaining condition was not verified. In this case, the opening was increased until the rotational speed was close to its nominal value.

The test procedure consists of five phases, where the MGT is operated by using:

- diesel for approximately 5 minutes. This phase allows MGT to be switched on and the thermal condition to be reached under the control logic set up for standard operation with diesel;
- the *first* SVO/diesel blend, for a time frame of approximately 10 minutes;
- diesel fuel for approximately 5 minutes. This phase allows the SVO residues to be removed from the pipes and the fuel supply system;
- by using the *second* SVO/diesel blend, for a time frame of approximately 10 minutes;
- by using diesel, to perform the final cleaning and switch off the MGT. This operation is conducted for at least 5 minutes and can be increased when the SVO/diesel ratio is progressively increased.

Diesel and vegetable oil blends were made in different percentages and by using three different types of vegetable oil: rapeseed, sunflower and soybean.

The total mass of each blend is 5 kg: the mass of diesel and SVO is varied in accordance with the selected percentage of SVO (5 %, 10 %, 20 %, 30 %, 60 %, 100 %), by using a precision balance.

The experimental measurements of EGT, compressor pressure ratio, CO and NOx are reported in Fig. 7 as a function of non-dimensional corrected rotational speed.

Figure 7 allows the direct comparison between the values with SVO blend feeding and the values with diesel feeding. The plotted data were obtained as an *average* of the measured values (characterized by a sampling time equal to ten seconds) for each of the phases described above, i.e. approximately 5 minutes for diesel and 10 minutes for SVO. This was particularly needed for emissions, due to the emission analyzer response delay.

As a general comment, it can be observed that by using blends of up to 30 % of SVO, the considered measurements are slightly modified compared to diesel feeding. In particular, at constant non-dimensional corrected rotational speed, the scatter of the values is probably due to measurement uncertainty. Otherwise, CO values are usually higher for SVO and diesel blends than for pure diesel.

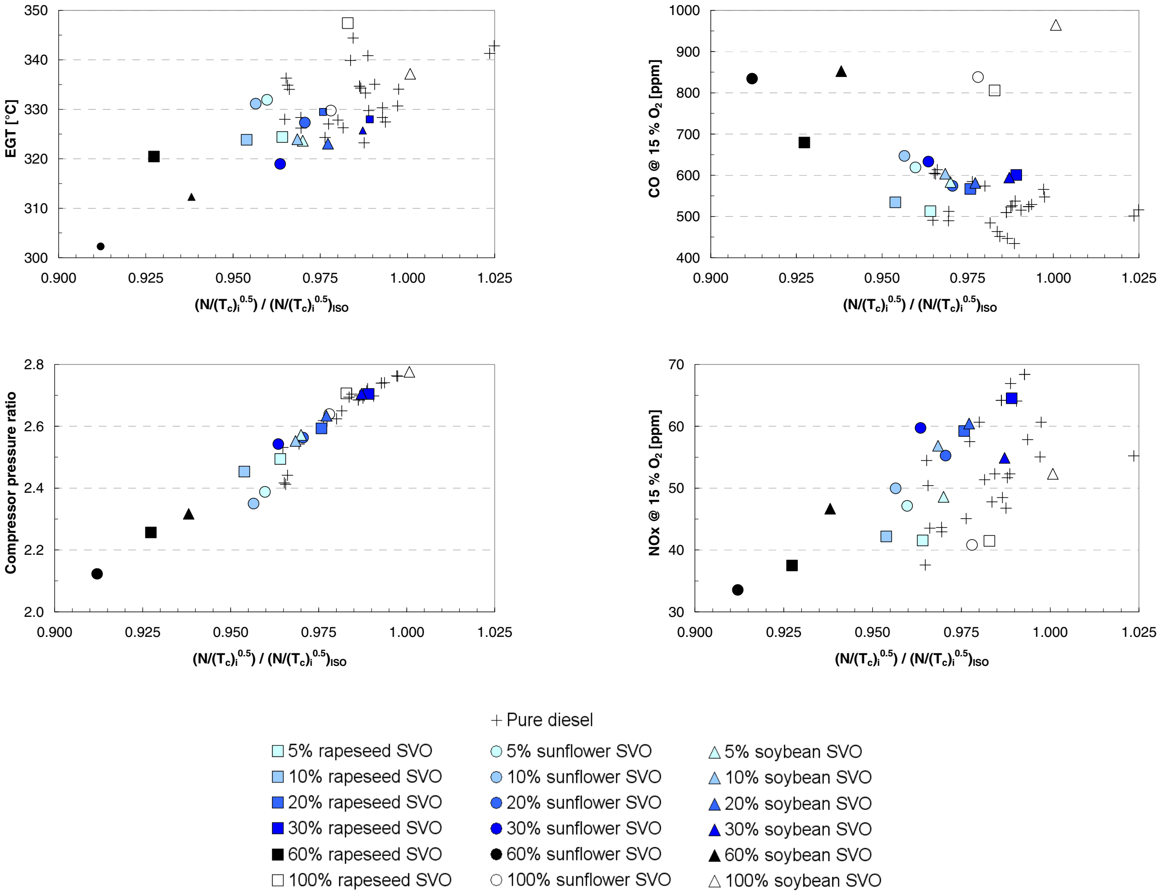

Figure 7. Measurements of EGT, compressor pressure ratio, CO and NOx vs. nondimensional corrected rotational speed (diesel and SVO blends)

Instead, if a blend of 60 % of SVO is considered, the SVO feeding leads the MGT to operate at a considerably lower corrected rotational speed, due to the decreased lower heating value of the injected fuel. This makes EGT, compressor pressure ratio and NOx decrease almost linearly, while CO increase is noticeable.

Finally, the MGT behavior at 100 % SVO feeding was also investigated. As previously highlighted, this was obtained by increasing the fuel flow valve opening to reach rotational speed values close to nominal value. The comparison of diesel feeding values in correspondence of similar non-dimensional corrected rotational speeds shows that EGT and compressor pressure ratio lie on the interpolation line of diesel feeding values, while NOx emissions seem slightly lower. Otherwise, CO emissions are considerably higher. It should be noted that, in all cases, the CO emissions increase as the SVO content in the blend increases, since the combustion system is designed for diesel feeding.

6. Conclusions

In order to evaluate the technical feasibility of the use of SVOs as gas turbine fuels, this paper reports the results of the experimental characterization of different vegetable oils, derived from dedicated crops (rapeseed, sunflower, soybean), and of blends of diesel and vegetable oil in different concentrations. Subsequently, this paper reports some experimental results obtained on a Solar T-62T-32 turbine fed by both straight vegetable oils and blends of diesel and vegetable oils.

The properties of pure or blended SVOs determined experimentally were elemental composition, lower heating value, density, specific heat and viscosity. It was found that:

- the elemental composition is almost the same;
- the lower heating value of rapeseed (37.2 MJ/kg) is slightly higher than that of sunflower (37.1 MJ/kg) and also of soybean (37.0 MJ/kg);
- once again, the specific heat of rapeseed was always higher than that of sunflower and also of soybean, in the considered range 20 – 160 °C;
- the difference among the density values of the three oils was negligible. The reduction of the density of the blend at 60 % diesel was equal to approximately 6 %, regardless of the type of oil;
- the dynamic viscosity varies greatly with temperatures up to the value of 50 °C, while for higher temperature values the variation is less pronounced. For the sunflower blends, a rule to decrease SVO viscosity was identified, by acting either on SVO temperature or the SVO/diesel blend (or by combining the two effects). For instance, it was observed that it is possible to keep SVO kinematic viscosity lower than 10 mm2/s even with pure sunflower SVO when the sunflower SVO is heated at 80 °C. Otherwise, if heated at 50 °C, an SVO kinematic viscosity lower than 10 mm2/s is granted only for blends with no more than 60 % of sunflower SVO.

It has to be highlighted that rapeseed SVO is the most preferable since it cannot be used in the food industry, while soybean SVO is the least preferable, since (i) it is also used as a foodstuff, (ii) the mechanical extraction is more difficult and therefore oil yield is lower and (iii) the produced gums and resins require greater effort for filtering and purification.

The experimental results obtained on the Solar T-62T-32 turbine fed by both straight vegetable oils and blends of diesel and vegetable oils highlighted some effects of the different fuels on micro gas turbine performance and pollutant emissions, such as CO and NOx. The micro gas turbine operation with 100 % straight vegetable oil did not highlight any particular problems, i.e. the combustion and noise seemed almost regular. In addition to the reduction of the rotational speed, as a consequence of the decrease of LHV at constant fuel flow, the only noticeable difference with respect to diesel feeding was the increase in the fuel injection pressure due to the higher density and viscosity of straight vegetable oils. In fact, in the case of pure straight vegetable oil feeding, the measured injection pressure was almost twice the injection pressure in the case of diesel. However, it should be noted that the MGT was operated for the time frame necessary for the experimental activity and therefore long-term effects of straight vegetable oil feeding are not considered in this paper.

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