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Article

Application of Biogas from Quinoa, Wheat, and Andean Guinea Pig Residuals as Biofuels for Gas Turbines

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Abstract: This article shows the effect that biogases obtained from crop residuals from the Andean region have on the performance of a whole medium-sized electrical-generating gas turbine. This technology could be used to supply electricity in energy-depressed areas where biogas is the only accessible resource. The gas turbine worked with higher efficiencies when the obtained biogases were used compared to natural gas. The biofuel that presented the highest efficiencies was the one obtained from wheat residuals alone. Despite this fact, this biofuel would be the most prone to create aerodynamic problems in the stages of the gas turbine. In this work, it was found that the addition of guinea pig manure to different crop residuals created biofuels less prone to create aerodynamic problems in the compression and expansion stages. In particular, the studied biofuel that had the most similar aerodynamic behavior to the design natural gas case was the one obtained from guinea pig manure and quinoa residuals. On the other hand, this biogas presented the lowest efficiencies of the studied biofuels. Despite this fact, this biofuel showed higher efficiencies than the natural gas case. In the gas turbine combustion chamber, all the studied biofuels operated at lower temperatures than the ones with natural gas, even in the high-power range. This would be an important feature for the running of the combustion chamber and the high-pressure turbine superalloys.

Keywords: biogas; gas turbines; Andean crop residuals; quinoa; wheat

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1. Introduction

This study was conducted to examine viable technologies in the Andean regions of South America where the conventional energy supply is inadequate, with limited or even nonexistent access to electricity and gas [1]. Presently, inhabitants of these areas heavily rely on organic fuels derived from their agricultural and livestock practices, such as firewood and dried animal waste, to fulfill their daily heating and cooking requirements [2]. It is imperative to implement performance optimization techniques that ensure economic, social, and environmental sustainability, while also integrating seamlessly into the traditional way of life and gaining acceptance from the local community [3]. Enhancing the availability of modern energy solutions in rural areas is crucial to addressing the challenges faced by these underserved regions and unlocking development opportunities [4–6]. The analysis of the introduction of biogas technology has been studied in different areas of the world [7]. However, the Andean zone presents particular atmospheric and raw material characteristics that require specific attention. One of the first steps to assess the viability of the implementation of technology based on gas turbines is to analyze their behavior when faced with new fuels [8], considering that determination methods for contaminants such as siloxane have been developed [9]. A low-cost process for emission abatement of biogas internal combustion engines has been developed, and this should be considered [10].

The economy of most Andean communities revolves around self-sufficient agriculture and family farming [11–13]. Their agricultural practices are predominantly agropastoral and are carried out in semi-arid, high-altitude regions, characterized by a diverse range of microclimates and ecosystems [14]. At higher elevations, the breeding of guinea pigs (*Cavia porcellus*) is one of the primary agricultural activities [15,16]. Guinea pigs are widely prevalent in rural Andean communities across Peru, Ecuador, Bolivia, and Colombia, having been domesticated between 2500 and 3600 years ago [17]. The production and utilization of guinea pigs hold significant importance for the area's sustainability, reflecting its traditional and ethnic/regional significance [14,18]. Unfortunately, the potential of guinea pig manure for energy purposes remains largely untapped, and these resources are undervalued [11,19]. However, exploring the bioenergy conversion of this specific waste is particularly compelling. One viable approach to address the energy needs of Andean communities is through the production of biogas from agricultural and livestock waste using anaerobic digestion (AD) technology. Additionally, wheat and quinoa are crops readily available in these regions.

Several studies have explored the application of anaerobic digestion to guinea pig manure [15,20]. These investigations highlight that anaerobic digestion (AD) holds significant potential for reducing farm waste while simultaneously offering an alternative means to fulfill local energy requirements by converting guinea pig manure into biogas [21].

The applications of biogas as a by-product of livestock activity can be focused on three different technologies: direct combustion in domestic kitchen burners or in gas boilers for heating; the use as biofuel in internal combustion engines; use as a biofuel in gas turbines.

The application of biogas obtained from the fermentation of guinea pig waste in gas turbines has been little studied to obtain electricity in economically disadvantaged Andean areas. Therefore, this research is of great importance, since it explores a field that is necessary to analyze.

The objective of this work was to evaluate this process through a computerized mathematical model to predict the behavior of this resource in gas turbines. This study uses the results of the evaluation of the productivity of co-digestion systems of guinea pigs, with wheat and quinoa previously tested by Meneses Quelal et al. [22].

When analyzing the working of a gas turbine after changing the fuel source, different aspects have been considered. A working point such as the design one with natural gas can be translated into a working behavior less prone to creating issues. This is particularly relevant when considering aerodynamic aspects. In this way, the new working points have been analyzed from the point of view of the new possible advantageous characteristics obtained by using biogas and considering the deviations as well from the machine's design point.

2. Materials and Methods

2.1. Biogas Production

In this study, the biogas under evaluation was derived from guinea pig (GP) manure collected from farms associated with Bolívar State University. The manure samples were carefully preserved in polyethylene bags at a temperature of 4 °C until further analysis. To prepare for co-digestion, wheat and quinoa straw residues were ground to a particle size of less than 3 mm using a universal cutter mill. Prior to being introduced into the biodigester, the substrates and co-substrates were thoroughly mixed in a kitchen blender to ensure sample uniformity. As an inoculum, sludge from a mesophilic anaerobic *digester* at the municipal wastewater treatment facility in Ibarra, Ecuador, was employed. Before commencing the fermentation tests, the inoculum was pre-incubated for 5 days at ambient temperature, ranging from 10 °C during the night to 25 °C during the day, to allow for the volatilization of residual biogas and depletion of readily available organic materials. The incubation process, in accordance with VDI 4630 [23] guidelines, aims to restrict methane production from the target substrates.

The biomethanization tests (BM tests) were conducted in batch digesters located at an altitude of 2512 m above sea level. These tests aimed to determine the maximum methane (CH_4) production of various substrates. The LDPE digesters used in the experiments had a total volume (V_T) of 3.5 m^3 and were tightly sealed throughout the digestion process. The reactors were filled to occupy 60% of the useful volume (V_U), while the remaining 40% constituted the gas or head volume (VG). All batch tests were carried out in triplicate to ensure the accuracy and reliability of the results. The biodigesters were maintained at a temperature of 5 °C during the night and 28 °C during the day, with a retention time of 40 days. Daily measurements were taken until the accumulated biogas production reached a stable level.

The evaluation of the BM tests was performed using two different substrate/inoculum ratios (SIRs): 1:1 g/g VS and 1:2 g/g VS. The process was conducted at mesophilic temperature, with the carbon-to-nitrogen (C/N) ratio determined based on the elemental analysis of the raw materials combination. The volume of biogas and methane produced solely by the inoculum was measured, and at the end of the experiment, the total inoculum production was mathematically subtracted from the total production of the substrates. This calculation allowed for the determination of the specific contribution of the substrates to the overall biogas and methane production.

2.2. Studied Gas Turbine

The simulations contained in this article were performed using GSP, release 11, by the Netherlands Aerospace Centre (NLR).

GSP is NLR's in-house simulation software dedicated to studying the performances of gas turbines and Brayton-derived power and propulsion systems. To perform this task, GSP performs the required calculations in a nondimensionalized way, averaging the fluid magnitudes of the cases over their cross areas and using 2 to 5 different variables. Efficiency maps can also be used in the case of compressors, turbines, and combustion chambers. The obtained solution at the outlet of one model's component is used to calculate the inlet conditions of the following one. The design point of the model is initially calculated in GSP, solving the nonlinear differential equations of energy, mass, and momentum balances [24,25]. The program then calculates the different machine's operating points, calculating the deviations to the previously obtained design point.

The employed general equations are shown in Equations (1) to (4) before being nondimensionalized and particularized.

The mass conservation equation is shown in Equation (1), where ρ is the density and $\vec{V}$ is the velocity.

$$\frac{\partial \rho}{\partial t} + div\left(\rho \vec{V}\right) = 0 \quad (1)$$

The momentum conservation equations [26] are shown in Equation (2), where τ represents the stress tensor, P is the pressure, and $\vec{g}$ is the gravitational acceleration.

$$\frac{\partial\left(\rho \vec{V}\right)}{\partial t} + div\left(\rho \vec{V}\vec{V}\right) = -grad(P) + div\left(\overline{\overline{\tau}}\right) + \rho \vec{g} \quad (2)$$

The energy conservation equation is shown in terms of the enthalpy in Equation (3), where ':' represents the contraction of two tensors, p represents the momentum change due to viscous dissipation and pressure, q_r represents the heat generation due to radiation, and $\vec{J_q}$ represents the heat flux density.

$$\frac{\partial(\rho h)}{\partial t} - \frac{\partial p}{\partial t} + div\left(\rho\vec{V}h + \vec{J_q}\right) + p : grad\vec{V} - div\left(p\vec{V}\right) = q_r \quad (3)$$

$\vec{J_q}$ is modeled according to Fourier's law. This law can be written as shown in Equation (4) if only the conduction heat is considered, which is appropriate for the studied case.

$$\vec{J}_q = \vec{J_q^c} = -\lambda gradT \quad (4)$$

$\vec{J_q^c}$ represents the heat flux density caused by conduction.

The different fuels studied in this article were tested in a gas turbine model representative of the medium-sized gas turbine range. This range is appropriate to study biofuels because it takes into account the current power demand needs (electrical) in society and the difficulties that may be found when producing biofuels.

Accordingly, the chosen gas turbine model to study the effect of biofuels was the General Electric LM2500PE. This gas turbine is an aero-derivative model derived from the GE CF6 turbofan engine family. This model has a single shaft, with its low-pressure turbine (component which is connected to an electricity generator) being a free power turbine. Its compressor has a 19.1:1 pressure ratio. This gas turbine provides, in nominal conditions, 23,292 kW when generating 60 Hz electricity [27].

This gas turbine uses natural gas as design fuel with a lower heating value (LHV) of 47,680 kJ/kg [28]. This natural gas has a lower LHV when compared to methane, which can be explained by the presence of inert components or larger hydrocarbons in it [28].

A summary of the deviations between the performed model and the real GE LM2500PE gas turbine is provided in Table 1. As can be seen, the model results and the real gas turbine data provided by the manufacturer [27] show a reasonable agreement.

Table 1. Manufacturer's LM2500PE gas turbine data [27] and LM2500PE model comparison.

	Power [kW]	Exhaust Mass Flow [kg/s]	Exhaust Temperature [K]
LM2500PE	23,292	69	806.15
Model	23,550.59	69.30	786.93
Deviation %	1.11	0.43	2.38

2.3. Biogas Characterization

The fuels studied in this article are shown in this section along with their lower heating values (LHVs). The effect of these biofuels on turbomachinery was tested in a medium-sized gas turbine model. This model could be considered representative of the medium-sized gas turbine range, which is an appropriate range for studying biofuels in current power generation. The way this machine works with these biofuels is compared to its work with its fossil fuel of design, which is natural gas.

Table 2 shows the studied biofuel compositions as well as their lower heating values (LHVs). Four different biofuels based on wheat and quinoa residuals were analyzed. On the one hand, biofuels produced alone with wheat and quinoa were studied. On the other hand, the effect of mixing the previously exposed agricultural residuals with guinea pig manure was also studied.

When analyzing Table 2, it can be noticed that the fuel obtained from 100% quinoa presents higher lower heating values (LHVs) than the fuel obtained from 100% wheat. It can also be noticed that the addition of guinea pig manure to the previously exposed agricultural residuals is translated into higher LHVs of the obtained biofuels. As shown, quinoa-obtained fuels present higher LHVs than their equivalent wheat-obtained fuels because of the higher CH_4 concentrations in the quinoa-obtained fuels. One of the possible reasons why quinoa may have given a higher calorific value than biogas obtained from wheat is the higher percentage of methane and hydrogen produced in fermentation. This is due to its carbon part of less crystallized polysaccharides than wheat, whose carbon is mainly present in cellulose and has a generally higher C/N ratio. Quinoa degradability is much better than wheat, in addition to presenting a more favorable nutritional balance for the microbial population.

Table 2. Studied biofuel compositions and lower heating values (mean ± standard deviation).

	% Volume CH_4	% Volume CO_2	% Volume H_2S	% Volume N_2	Lower Heating Value (LHV) [kJ/kg]
Wheat Residuals	57.00 ± 1.26	42.42 ± 2.36	0.27 ± 0.02	0.31 ± 0.12	16,604.88
Quinoa Residuals	65.08 ± 0.98	33.95 ± 2.36	0.35 ± 0.09	0.62 ± 0.11	20,541.66
Guinea Pig Manure—Wheat Res. 75:25	66.73 ± 2.11	32.14 ± 0.25	0.32 ± 0.08	0.81 ± 0.22	21,746.17
Guinea Pig Manure–Quinoa Res. 50:50	69.00 ± 1.02	29.9 ± 0.99	0.38 ± 0.12	0.72 ± 0.32	22,822.33

On the other hand, secondary emission levels should be pointed out, as these contaminants may cause problems to the lifetime of the gas turbines, too, but also may oblige installation of a waste gas treatment system. It can be seen that the H_2S composition is lower than 0.40% of the volume, and N_2 lower than 1%. Components, such as NH_3, NO_x, N_2O, light VOCs (to the molecular weight of benzene), and heavy VOCs with higher molecular weight, should be considered, but they could not be measured because the infrastructure in the Andean areas only allowed for analysis of the components in Table 2.

In Table 3, the composition of the substrates and the inocula used are indicated.

Table 3. Characterization of substrates and inocula mean (standard deviation).

Parameters	Units	GPM	QS	WS
TS	%	33.9 (1.7)	87.0 (0.1)	92.6 (0.1)
VS (% ST)	%	72.6 (1.1)	58.4 (1.5)	77.2 (0.9)
Ashes	%	13.1 (0.1)	30.3 (1.4)	11.8 (0.1)
N	%	2.3 (1.0)	2.2 (0.9)	1.7 (0.7)
C	%	39.5 (1.2)	30.7 (1.7)	48.9 (1.6)
H	%	4.6 (0.5	6.4 (0.9)	6.1 (0.5)
O	%	39.7 (1.2)	29.8 (1.7)	31.1 (1.6)
S	%	0.4 (0.0)	0.6 (0.1)	0.5 (0.0)
C/N	-	15.3 (0.8)	12.0 (0.9)	29.6 (0.8)

NOTE: GPM (guinea pig manure), WS (wheat straw), QS (quinoa straw). The data in brackets are the standard deviations.

3. Results

This section presents the results of different gas turbine (GT) important parameters. The shown parameters resume the overall working in terms of efficiency but also analyze the fuel consumption and stability of the working (aerodynamic-related parameters).

Figure 1 shows how temperatures at the combustion chamber outlet evolve when the gas turbine changes the provided output power. These temperatures are important to determine if the gas turbine components would have to face overheating issues. The combustion chamber outlet is also the inlet of the high-pressure turbine (component of the gas turbine right after the combustion chamber). As can be seen, all the studied biofuels in this article operate the gas turbine at lower outlet combustion temperatures than the design natural gas fuel. This fact would make the high-pressure turbine work less demanding from the employed superalloys' point of view.

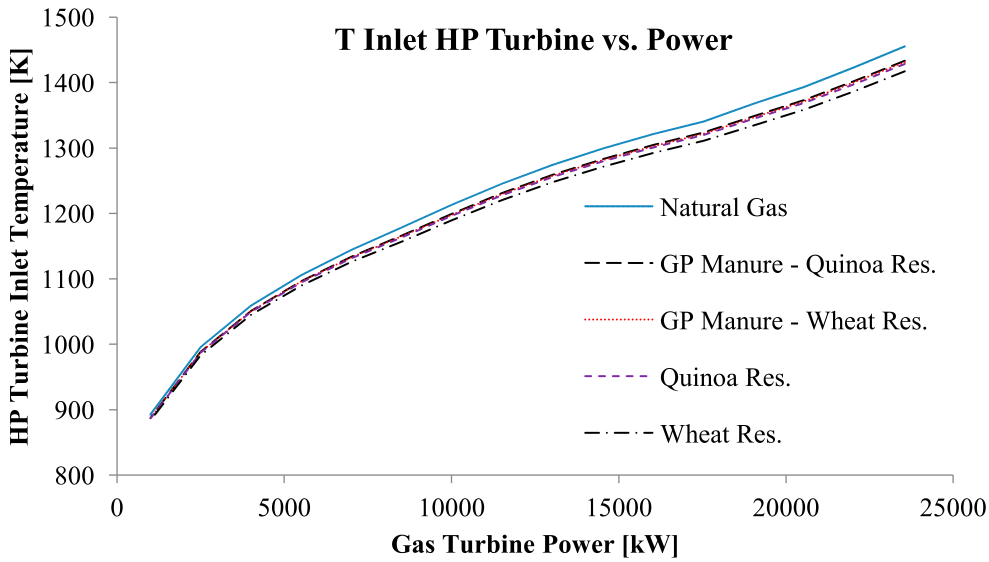

Figure 1. Gas turbine high-pressure turbine inlet temperatures vs. power.

The fuel obtained from the mixture of guinea pig manure and quinoa residuals (GP Manure–Quinoa Res.) is the fuel with the highest outlet combustion temperatures of the studied biofuels. Despite this fact, this fuel still operates the gas turbine at lower outlet combustion temperatures than the design natural gas case.

The fuel obtained from the mixture of guinea pig manure and wheat residuals (GP Manure–Wheat Res.) operates the gas turbine at slightly lower temperatures than the fuel obtained from the mixture of guinea pig manure and quinoa. It should be remembered at this point that the GP Manure–Quinoa Res. fuel was obtained with a manure–quinoa ratio of 50:50, while the GP Manure–Wheat Res. fuel was obtained with a manure–wheat 75:25 ratio. In this way, the manure–wheat fuel would need a lower percentage of agricultural residuals than the manure–quinoa fuel.

The 100% quinoa-residual-obtained fuel (Quinoa Res.) operates the gas turbine at similar combustion outlet temperatures to the cases obtained from the mixture of guinea pig manure. This case drives the gas turbine at slightly lower temperatures than the GP Manure–Wheat Res. fuel case.

The 100% wheat-residual-obtained fuel (Wheat Res.) is the case in which the temperatures at the outlet of the combustion chamber are the lowest of the studied cases. Accordingly, this would be the fuel with which the high-pressure turbine would be operated in the least demanding way.

Figures 2 and 3 show the obtained gas turbine efficiencies when compared to the gas-turbine-provided power. Figure 3 shows a detail of Figure 2 for the high-power range. High-efficiency levels are desirable. As can be noticed, all the studied biofuels in this article operate the gas turbine at higher cycle efficiencies than the design natural gas case. Although biofuels have a lower LHV than natural gas, this fact may be caused by the structural limitations in the reachable maximum temperatures in Brayton cycles compared, i.e., with Otto cycles. In Brayton cycles, higher LHV values are not directly translated into higher maximum cycle temperatures, because of the dilution role, and the obtained higher efficiencies come from the overall balance of the whole machine.

The GP Manure–Quinoa Res. fuel is the case in which the obtained cycle efficiencies are the lowest ones of the studied biofuels, although they are higher than the design natural gas fuel ones. The GP Manure–Wheat Res. fuel, on their side, operates the gas turbine at slightly higher efficiencies than the GP Manure–Quinoa Res. fuel.

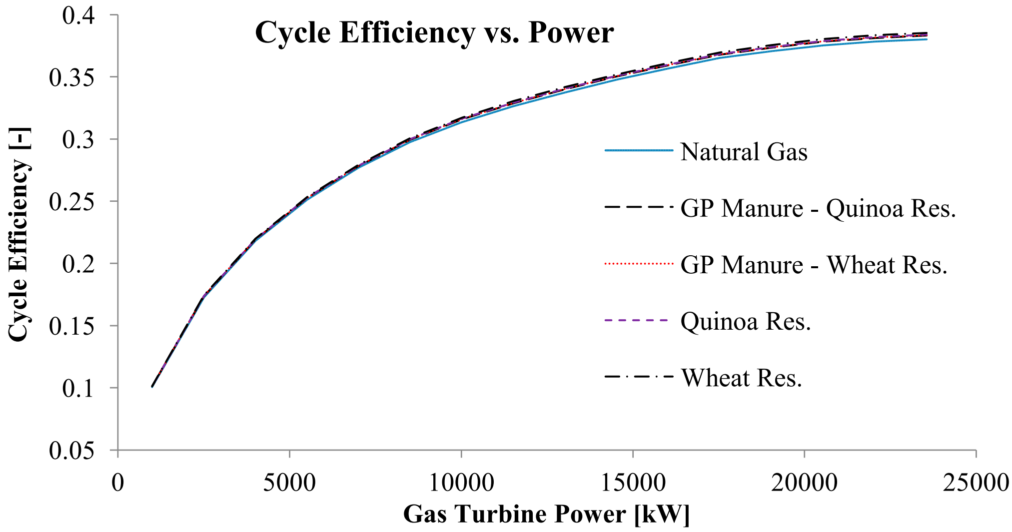

Figure 2. Gas turbine efficiency vs. gas turbine power.

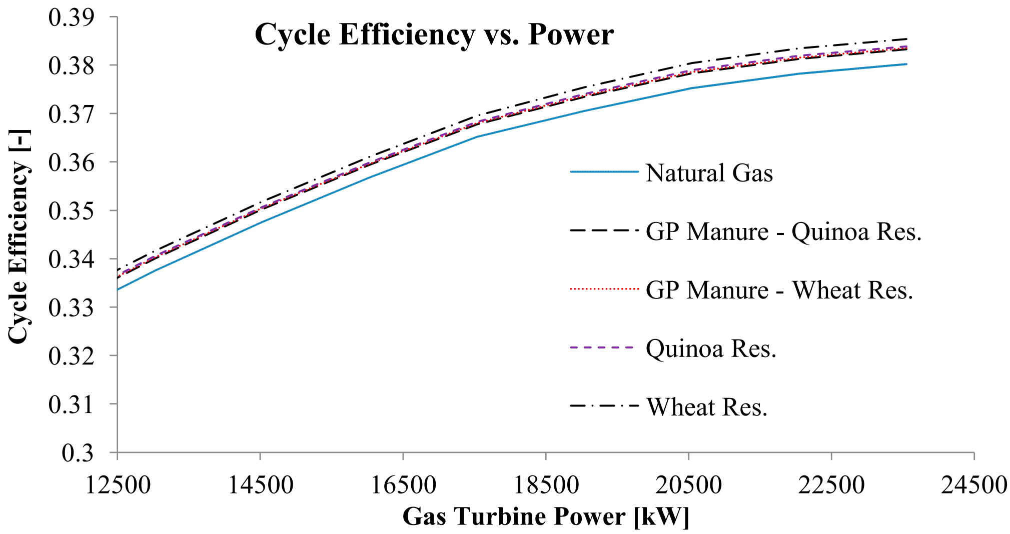

Figure 3. Detail of Figure 2 for the high-power range.

The 100% quinoa-obtained biofuel operates the gas turbine at slightly higher efficiencies than the fuels obtained from manure mixtures. Despite this fact, the 100% quinoa-obtained biofuel is a case with intermediate efficiency levels between the manure–crop residual mixtures and the wheat residual case but closer to the manure mixture cases.

The 100% wheat-obtained biofuel would be the case in which the gas turbine would work with the highest efficiencies of the studied cases. The reason for this is the same as the previously exposed comparison between biofuels and natural gas.

Figures 4 and 5 show the gas turbine's inlet mass flows when the obtained output power is changed in the different studied cases. Figure 5 shows the inlet mass flows for the high-power range. This magnitude is directly connected to the velocities the compressors would have to face. Accordingly, as close a behavior as possible to the design gas turbine values with natural gas is desirable to avoid possible working issues.

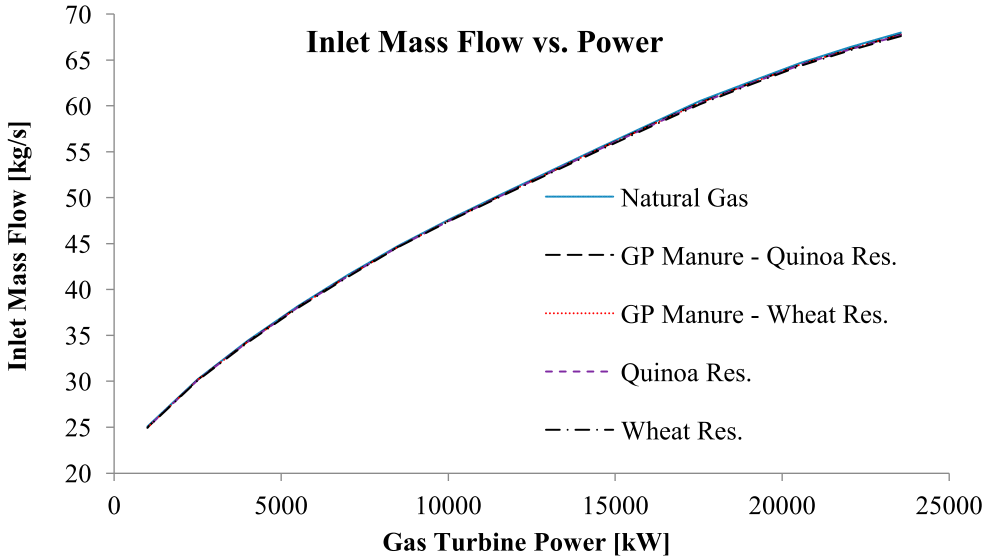

Figure 4. Gas turbine inlet mass flow vs. gas turbine power.

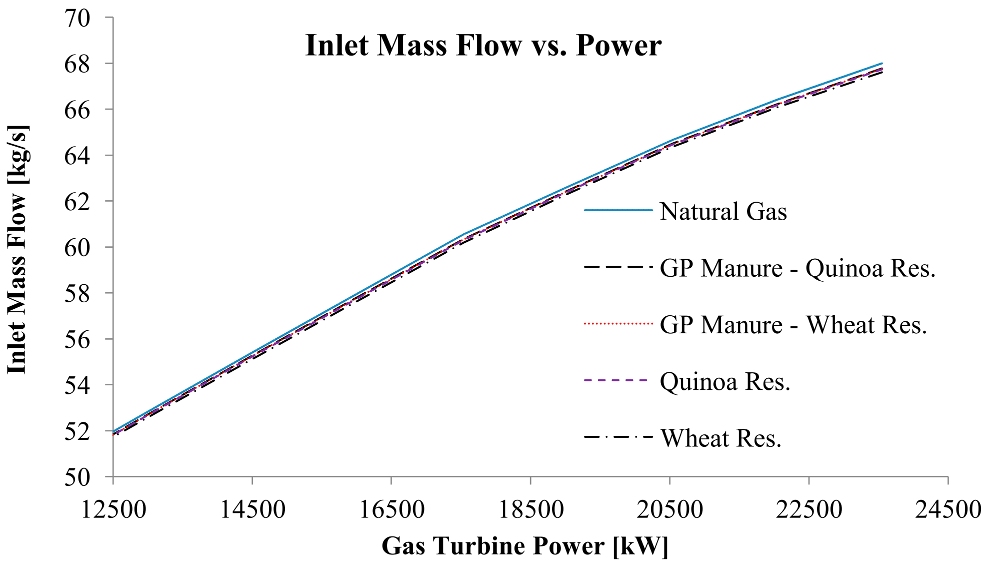

Figure 5. Detail of Figure 4 for the high-power range.

As can be noticed, all the studied biofuel cases present minor deviations compared to the design natural gas case. As was previously explained, when talking about aerodynamics, as close a behavior as possible to the design with natural gas may be translated into a working less prone to creating aerodynamic issues. Since the inlet mass flow directly affects the velocity working-fluid flow field, closer values to the design ones are positive to obtain a correct machine working. Accordingly, no aerodynamic problems are expected in the compressors when employing the studied biofuels.

The case in which the deviations are minimal compared to the design case is the fuel obtained from the mixture of guinea pig manure and quinoa residuals (50:50). The variations, in this case, are almost identical to the obtained ones when mixing guinea pig manure and wheat residuals (75:25) to obtain the fuel.

The fuel obtained from 100% quinoa residuals presents almost the same deviations as those obtained when mixing quinoa or wheat with guinea pig manure. The obtained deviations in the 100% quinoa case are slightly higher than those obtained in the manure mixture fuel cases.

The fuel obtained from 100% wheat residuals presents the highest deviations of the studied cases. Despite this fact, these deviations are close to the ones of the other studied biofuels.

Figure 6 shows the fuel consumption for the different studied cases. This magnitude would be important to evaluate economic aspects as well as the interactions with the biofuel production and storage systems. As can be noticed, all the studied biofuels present much higher fuel consumption than the design natural gas case. This fact is especially noticeable for the high-power range.

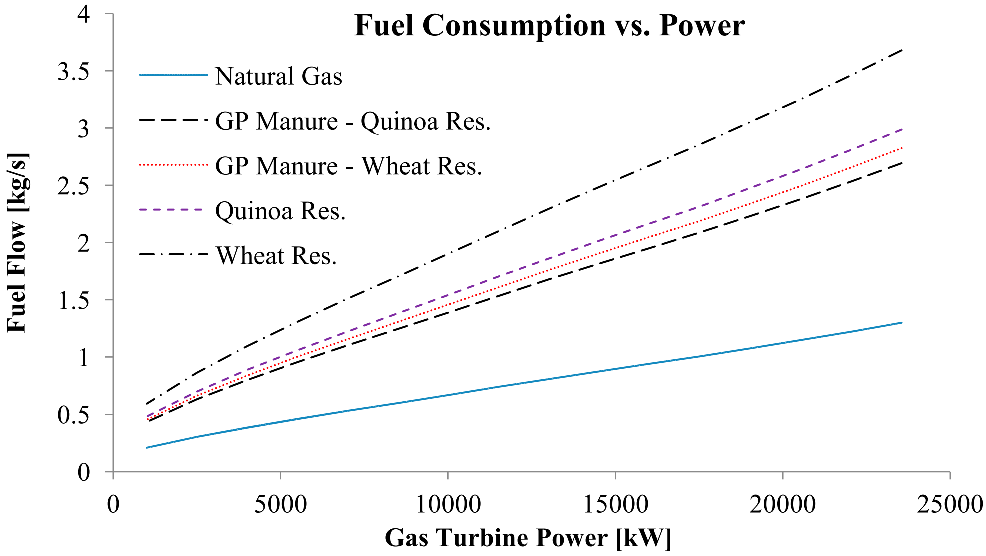

Figure 6. Fuel consumption of the studied cases.

The fuel obtained from the mixture of guinea pig manure and quinoa residuals is the biofuel case with the most similar fuel consumption to the natural gas design case. However, the fuel consumption for this case is much higher than for those with natural gas. This fact is especially noticeable in the high-power range.

The fuel obtained from the mixture of guinea pig manure and wheat residuals is the second-best case in terms of proximity to the natural gas fuel consumption. Although this case has almost the same fuel consumption as the GP Manure Quinoa Res. fuel for the low-power range, the differences are more clearly observed for the high-power range.

The 100% quinoa-obtained fuel is the third-best case with the most important deviations compared to the natural gas case. Although this fuel was obtained without being mixed with GP manure, its behavior is similar to the ones of the GP cases. Nevertheless, these deviations can be found more importantly in the high-power range.

The fuel obtained from 100% wheat residuals is the case with the most important deviations compared to the natural gas fuel consumption. These deviations are important when compared to the other biofuel cases, especially in the high-power range.

The effects that the differences in the fuel flow, as well as the differences in the obtained combustion temperatures, have on the aerodynamic working of the machine are explained later in this article when analyzing the nondimensionalized high-pressure turbine inlet velocities.

Figure 7 shows the nondimensionalized velocities at the inlet of the high-pressure turbine (HPT). Changes in the velocities at the inlet of the high-pressure turbine can mean a behavior more prone to create aerodynamic problems in the blades of this component. As was previously explained, when talking about aerodynamics, as close a behavior as possible to the design with natural gas may be translated into a working less prone to creating aerodynamic issues. This component (HPT) of the gas turbine is located right after the combustion chamber. In this way, any change in the combustion chamber would directly affect this component and the following ones.

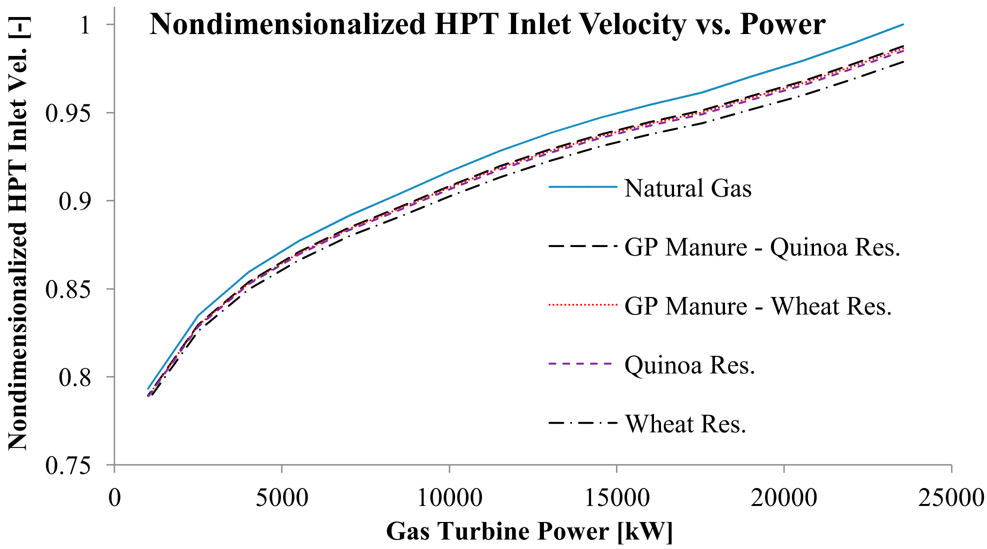

Figure 7. Nondimensionalized high-pressure turbine inlet velocities vs. gas turbine power.

The GP Manure–Quinoa Res. fuel is the biofuel case with the most similar velocities to the natural gas case. Despite this fact, noticeable differences in this fuel can be found compared to natural gas in the high-power range.

The GP Manure–Wheat Res. fuel is the second fuel in terms of deviations compared to the natural gas case. However, its behavior is almost identical to the GP Manure–Quinoa Res. fuel.

The fuel obtained from 100% quinoa is the third case in terms of deviations from the natural gas case. This fuel has a very similar behavior compared to the GP-obtained cases. The 100% wheat-obtained fuel is the case with the highest deviation from the natural gas case. Accordingly, this would be the fuel more prone to creating aerodynamic problems in the blades of the high-pressure turbine, in case these problems would appear.

4. Discussion

Biofuels have been proven in other works as promising fuels to operate gas turbines avoiding, at the same time, greenhouse gas emissions [29]. At the same time, biogases have been studied as a possible option to be upgraded, obtaining in this way a natural gas substitute [30]. The perspective taken in this work, however, studies the effect that crude biogases obtained from available sources in the Andean region would have on power-generating gas turbines. In particular, this work studies the effect of biogases obtained from crop residuals available in that region. Other valid alternative fuels that can be used in gas turbines in this region would have been biogases from sewage treatment plants [31]. This previous reference employed a modeling point of view to perform the studies, with the anaerobic digestion being modeled using the ADM1 model. Similar studies were performed by other authors analyzing the use of biogases applied to micro gas turbines when oriented to power generation in India [32]. The previous reference analyzed an existing facility in India built with two micro gas turbines but with only one of them working and the other on standby. During the working of this facility, no problems were encountered in the working of the gas turbines. However, other parts of the facility such as the cleaning section did encounter several issues during their work. Other articles have experimentally studied the effect that biofuels would have on the combustion chambers of micro gas turbines [33,34]. To perform their studies, in reference [29], the authors employed synthetic biogas (carbon dioxide and methane) in a combustion test rig. They found stable biogas combustion for gas turbines, even when significantly varying the biogas composition and the gas turbine nominal power. In reference [30], the authors designed, manufactured, and tested a combustor for micro gas turbines adapted to be used with biofuels. The authors paid special attention to the premixing of the fuel and air to reach low nitrogen oxide emissions.

Other authors studied, at the same time, the generated emissions [35] and the effect of the CO_2 content in the fuel. In the previous reference, the authors employed an experimental combustion facility composed of an air tank, an air heater, the combustor itself, and the exhaust system, with the different facility parts connected to the data acquisition system. In the following reference [36], the authors employed a facility composed of a centrifugal fan, a combustor, and a discharge valve. The experiment was performed at atmospheric pressure. In this case, the authors employed optical methods to perform the different measurements. In this work, however, the point of view taken is the performance study of the whole gas turbine instead of a detailed study of a single component. Other works have numerically studied, in this context, micro gas turbines [37]. In this case, a medium-sized power-generating (electrical) gas turbine was studied through computational models. This size of gas turbines would take into account the current needs of electrical markets as well as the possible limitations in producing biofuels. Although computational results could be less accurate than direct experimental studies on gas turbine components, the knowledge of the working of a whole gas turbine is valuable. Other works numerically studied different modifications of gas turbines (Brayton cycle) to adapt them to biofuel use [38]. In this case, gas turbines without modifications are analyzed to allow for the direct reuse of existing turbomachinery. Numerical studies have been proven as a valuable way to study combustion in gas turbines when using biofuels [39]. The previous reference employed CFD methods to perform the combustor analysis. Given the numerical cost of CFDs when studying a single gas turbine component, i.e., a low-pressure turbine [40], or when studying combustion related to carbon capture processes [41], CFD methods were not considered as suitable in this work since a whole gas turbine is studied. Other authors have conducted valuable non-CFD numerical studies of gas turbine performance analysis [42] as well as combustion and control processes with biofuels [43]. As explained above, a non-CFD numerical performance study of a whole medium-sized power-generating (electrical) gas turbine using biofuels available in the Andean region was performed in this article, as explained in the Methods sections.

A possible direction to develop this research topic may be the study of other crop residuals that may be found in the Andean region. In that sense, the study of amaranth crop residuals may be a possible new line to develop.

5. Conclusions

This work demonstrates that Andean regions have the potential to generate fuels (biogases in this case) using their own resources and that these biogases can be used in power generation with acceptable conditions and are comparable to the use of natural gas.

This article shows the effect that biogases obtained from crop residuals from the Andean region have on the performance of a whole medium-sized electrical-generating gas turbine. As shown above, the studied gas turbine presented lower temperatures at the outlet of the combustion chamber than the ones with natural gas as fuel. This fact may be beneficial for the superalloys of the combustion chamber itself and the low-pressure turbine since they would work in a less demanding way. All the studied biogases operated the gas turbine at higher efficiencies than the ones with natural gas. In particular, the biofuel that presented the highest efficiencies was the one obtained from wheat residuals. The biogas that presented the lowest efficiencies was the one obtained from the mixture of guinea pig manure and quinoa residuals. Despite this fact, this biofuel presented higher efficiencies than the ones with natural gas. The rest of the studied biofuels presented slightly higher efficiencies than this previous case. Concerning the working of the turbine stages, all the studied biofuels presented lower velocities than the natural gas case at the inlet of the high-pressure turbine. In particular, the biofuel case that presented the highest deviations was the one obtained from wheat residuals. The biofuel case that presented the lowest deviations was the one obtained from the mixture of guinea pig manure and quinoa residuals. It can be noticed that the addition of guinea pig manure to wheat and quinoa crop residuals makes the turbine stages work more similarly to the working with the design natural gas case. The inclusion of wheat residuals in the biofuel mixture, particularly, had a significant impact. It resulted in a behavior that closely resembled that of natural gas, which, in turn, reduced the likelihood of encountering aerodynamic issues. This improved behavior in terms of aerodynamics was observed specifically during the turbine stages. The addition of guinea pig manure to crop residuals contributed to the creation of biofuels with enhanced aerodynamic characteristics, resulting in smoother operations during the turbine stages. Similarly, this positive effect extended to the compression stages, further highlighting the benefits of combining guinea pig manure with crop residuals in terms of aerodynamic performance.

The regions where the experiments were carried out are composed of families of five to seven members. They live in separate houses (500 m), dedicated to pigs and guinea pigs, and small plots of wheat and quinoa (500 m^2).

The fermentation experiments carried out with waste in the Andean zone in the province of Guaranda (Ecuador) indicate that a family is capable of producing 1 m^3 of biogas per day from agricultural wastes, which allows it to provide electrical energy and gas consumption to cook food.

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