

Viscosity Control of Vegetable Oils Applied to the Diesel Cycle Generator Group in an isolated community in the Amazon

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Abstract — This article proposes a sustainable way to generate electricity for isolated communities in the Western Amazon, using vegetable oil, heated in a heating tank, as a fuel to diesel cycle generators. Vegetable oil under high temperatures reaches a viscosity like diesel oil and does not cause damage to the generator's starting and fuel injection systems. Through mathematical and computational models, it is possible to control the temperature and the oil viscosity through sensors to reach a complete combustion of the fuel. All of this contribute to the development of the population of isolated communities that suffer without access to electricity.

Keywords— Diesel cycle, Isolated Communities, Renewable energy, Vegetable oil, Sustainability.

I. INTRODUCTION

Brazilian electricity matrix is mainly composed by renewable sources, with emphasis on the hydraulic generation that accounts for 65.2% of all domestic supply.

Renewable sources account's for 80.4% of the domestic supply of electricity in Brazil, which is the result of domestic production and imports, which are essentially from renewable sources [2].

Electricity energy production and transmission are coordinated by the National Electric Operator - NEO. Only 1.7% of the country's energy production is outside the NEO. This portion is composed of small isolated systems. There are approximately about 250 isolated locations in Brazil, most of them in the Amazon region.

The great distances involved, plus the access difficulties and the low power demand, results in those isolated systems.

Diesel generator are the main source of power on those isolated systems.

This difficulty in supplying electricity does not allow the development of economic activities and the generation of jobs in isolated communities. Electric energy represents a way of improving the living conditions of the population

and social inclusion for isolated communities, through the possibility of creating productive means in these areas [3].

The use of local natural resources to generate electricity allows the creation of jobs, the qualification of the local labor force, the fixation of man in the countryside, and the enhancement of local biodiversity.

Brazil has a huge diversity of oil plants, both native and exotic, admirably adapted to Amazon due to favorable climatic conditions. Highlighting some cultivable species such as oil palm, *Elaeis guineensis*, an exotic species of African origin, perfectly adapted to Amazon's climatic conditions, has the advantage of having high oil productivity (3 to 5 tons of oil per hectare). Babassu is a species that can be found on average 200 plants/ha, where each plant has bunches with about 150 to 300 fruits. The average productivity of babassu is about 5 tons of fruits/ha/year, being possible to extract 400 kg of vegetable oil/year.

Buriti has an average fruit production of 200 kg, making it possible to obtain 20 kg of oil/plant/year. Considering the average of 250 plants/ha, an annual total of 5.000 kg of vegetable oil/ha/year can be obtained.

The use of vegetable oils starts by extracting them. The seeds are dehydrated and taken to hydraulic presses. After

the extraction of vegetable oil, filtration is carried out. The vegetable waste produced by the pressing process can be used to feed animals or to make charcoal to be burned in kilns, bakeries, and so on. Thus, the demand for firewood is reduced, avoiding deforestation.

The direct use of vegetable oils in diesel engines causes problems due to their high viscosity and low volatility. The high viscosity is responsible for the incomplete combustion of the oil, resulting in the formation of carbon deposits on the injector nozzles and on the cold walls of the cylinder. To circumvent these problems, thermochemical processing is used, in which transesterification and cracking stand out. It is also possible to use a mixture of diesel oil with up to 30% vegetable oil in conventional diesel engines with relative success, without the need to make mechanical changes to the engine [1], [3].

There is only one engine, developed by the German firm DMS, with Elsbett technology, which directly uses vegetable oil without the need for thermochemical processing. This multi-fuel engine, which is just a diesel engine with some modifications to the cylinder geometry and the fuel injection system, has already been used in some locations with relatively satisfactory results. However, the hours of continuous operation have not yet been counted to know the real performance of this engine with this type of fuel. [3].

This article introduces a vegetable oil viscosity control device *in natura* avoiding mechanical problems in the engine, such as nozzle clogging, incomplete fuel burning.

It is a low cost, simple and easy solution that can be handled by the local community. Thus, it represents one of the possible alternatives for supplying electricity to isolated systems. Vegetable oil has characteristics that allow partial and even total replacement of conventional diesel oil in engines that generate electricity.

II. MATHEMATICAL MODELING OF THE HEATING TANK

To reduce the viscosity of vegetable oil and avoid mechanical problems in the engine, just heat the oil to the appropriate temperature to reduce the viscosity and the oil and air mixture becomes richer in fuel. The viscosity and temperature of fluid are intrinsically related. Thus, in order to preheat the fluid, in order to avoid cold starting and to guarantee a constant viscosity and adequate for the proper functioning of the diesel cycle engine, a tank is used in which, initially, the fuel will be heated through electrical resistances and, later, by the exhaust gases of the engine. Depending on the physical-chemical characteristics of the

oil, the heat that must be offered to the tank will sometimes be higher, and sometimes it will be lower, in addition, climatic conditions, such as ambient temperature, will also be a variable to consider. The analysis of a dynamic system, that is, investigating and analyzing the behavior of a process in response to various types of variable inputs could, in this case, be carried out by annotating the results through an empirical process, changing the inputs of the variables and verifying the changes in the output. However, for chemical processes, such as changing the viscosity of the oil, once the system has been disturbed, it would take a long time before the oil could return to similar initial conditions and, again, introduce different amounts of heat to obtain other viscosity values. Mathematical modeling then emerges as an alternative to represent the dynamic process and, although theoretical analyzes only provide knowledge about the behavior of the idealized process, it proved to be especially useful in understanding and characterizing real behavior.

Therefore, it is important to be familiarized with the mathematical tools that allow the description of the equations of the dynamic system and dimension the variables, in addition to determining the transfer function of the process.

To develop a mathematical model for heating a tank, the following situation is considered: an oil of initial temperature T_i is available at a mass input rate, ρF . It is desirable to heat this oil to a higher temperature T_r .

The oil flows into a well-stirred tank, equipped with a heating device. It is assumed that agitation is sufficient to ensure that all the oil in the tank will have the same temperature, T , which is the outlet temperature and is related to the kinematic viscosity, ν_c . The heated oil is removed from the bottom of the tank at the same inlet flow rate, ρF , now as the product of the present heating process. Under these conditions, the oil mass retained in the reservoir remains constant over time, and the oil outlet temperature is the same as that of the oil in the tank. For a satisfactory project, this temperature must be the desired temperature at the outlet, T_r .

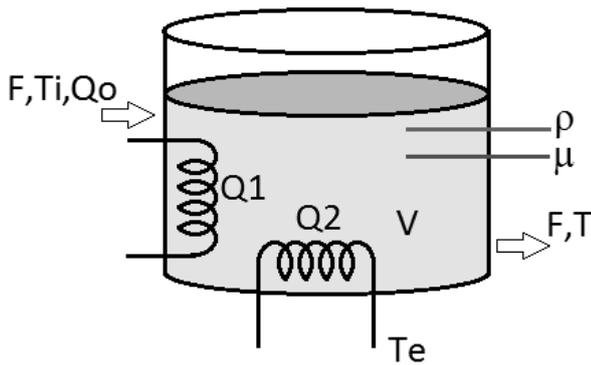


Fig.1 - Heating tank stirred. Source: [11].

It is assumed that the variation in the amount of oil heat, the specific density and the latent heat of vaporization, C_p , ρ and λ , respectively, do not vary significantly with temperature, that all the heat from the heater is transferred to the oil and none heat is retained in the serpentine and that the thermal losses to the atmosphere are negligible.

Where:

- T, T_i e T_r = Exit temperature, inlet temperature, and reference temperature, respectively, given in Kelvin (K);
- ρF = Input mass rate = Output mass rate, given in kg/s.
- C_p = Variation in the amount of heat: $Q_{1,2} - Q_0 / T - T_i$, given in J/K.
- ρ = Specific density, given in kg/m^3
- λ = Latent heat of vaporization, given in J/kg.
- ν_c = Kinematic viscosity, given in m^2/s .

The general mass balance equation is given by:

- Mass rate accumulated in the tank = $\frac{d}{dt}(\rho V)$
- Mass entry rate = ρF
- Mass output rate = ρF

As there is no mass generation or consumption in this system, the general mass balance equation will be given by:

$$\frac{d}{dt}(\rho V) = \rho F - \rho F \tag{1.0}$$

And based on the assumption that the specific density ρ is constant:

$$\frac{dV}{dt} = 0 \tag{2.0}$$

Therefore, it is concluded that the volume of the fluid, V , given in m^3 , will be constant in the dynamic process considered, since, in the same way, it is assumed that the mass rates of entry and exit are equal.

For this system, we must note that, although the total energy is the sum of the internal energy, the potential energy, and kinetic energy, the rate of energy accumulation involves only the rate of change of the internal energy. This is due to the simple reason that the tank is not in motion, thus eliminating the participation of any kinetic energy and since there is also no change in the position of the tank, the rate of change of the potential energy will also be zero. Thus, it is assumed:

- Rate of energy accumulation in the tank

$$\rho C_p \frac{d}{dt}[V(T - T_r)] \tag{3.0}$$

- Input heat rate

$$\rho F C_p (T_i - T_r) \tag{4.0}$$

- Rate of heat input through heating steam

$$\lambda Q \tag{5.0}$$

- Output heat rate

$$\rho F C_p (T - T_r) \tag{6.0}$$

Thus, the general energy balance equation is:

$$\rho C_p \frac{d}{dt}[V(T - T_r)] = \rho F C_p (T_i - T_r) + \lambda Q - \rho F C_p (T - T_r) \tag{7.0}$$

Simply put, we have:

$$\rho C_p V \frac{dT}{dt} = \rho F C_p (T_i - T) + \lambda Q \tag{8.0}$$

From the mass balance, it is known that V is constant, so the equation can be simplified to:

$$\frac{dT}{dt} = -\frac{1}{\theta} T + \frac{\lambda}{\rho V C_p} Q + \frac{1}{\theta} T_i \tag{9.0}$$

Where $\theta = V/F$ is the residence time of the tank.

Equation 9 is a model of a differential equation that represents the temperature variation over time inside the agitated heating tank as a function of the inlet temperature, the latent heat rate of vaporization, the residence time of the tank, among other parameters physicists.

The model in terms of deviation variables must be considered in the modeling.

A process is considered to be in steady state when none of the variables are changing over time.

In the desired steady state, the energy balance throughout the heating process can be written as follows:

$$0 = -\frac{1}{\theta}T_s + \frac{\lambda}{\rho V C_p} Q_s + \frac{1}{\theta}T_{is} \quad (10.0)$$

Where the subscript s is added to indicate a steady-state value. And defining the variables in equation 10 by the deviation variables:

$$x = T - T_s; \quad u = Q - Q_s; \quad d = T_i - T_{is}$$

Subtraindo a equação 9 da equação 10:

$$\frac{dx}{dt} = -\frac{1}{\theta}x + \beta u + \frac{1}{\theta}d \quad (11.0)$$

Where $x(0) = 0$ is the initial condition itself, if $T = T_s$ and $t = 0$. Note that this case is a tank heating model in steady-state, so the output variable y is equal to variable x , that is, $y = x$.

Rewriting the mathematical model in terms of deviation variables and considering the model in steady state causes the initial conditions of the deviation variables to be zero. Thus, the Laplace transform can be performed without absorbing external values related to the initial conditions.

The Laplace transform of equation (4.12) will be,

$$sY(s) = -\frac{1}{\theta}Y(s) + \beta U(s) + \frac{1}{\theta}D(s) \quad (12.0)$$

Now, this is a mathematical model for the dynamic system of the heating tank, in the transform domain, and can be rearranged to become an algebraic expression of $y(s)$ in terms of its dependencies $u(s)$ and $d(s)$

$$Y(s) = \left(\frac{\beta\theta}{\theta s + 1}\right)U(s) + \left(\frac{1}{\theta s + 1}\right)D(s) \quad (13.0)$$

If we introduce the following equations:

$$g(s) = \frac{\beta\theta}{\theta s + 1} \quad (14.0)$$

$$g_d(s) = \frac{1}{\theta s + 1} \quad (15.0)$$

Soon Equation (4.13) becomes:

$$Y(s) = g(s)U(s) + g_d(s)D(s) \quad (16.0)$$

Equations 14 and 15 are called transfer functions and equation 13 is a model of the transfer function for agitated heating tanks. Equation 16 is a general expression for transfer function models in the Laplace transform domain.

The vegetable oil heating tank will use a probe called Lambda, which is a sensor that performs the measurement of gases, and these data are used by the injection module to obtain the stoichiometric point. That is the ideal mix between vegetable oil and oxygen.

The model description assumes that the chemical reactions are in equilibrium and that the exhaust gases obey the Law of Ideal Gases:

$$pV = nRT \quad (17.0)$$

R is assumed to be 8,314 J / mol. K (universal gas constant), that the total pressure of the system remains constant and that pressure is called p , that the temperature of the ambient air is equal to the temperature of the exhaust gas and remains constant at a temperature $T = 973,15$ K.

To determine the oxygen concentration, the molar fraction of the gas composed of 6 gases is used, Equation 18.

$$X_{H_2} + X_{O_2} + X_{H_2O} + X_{CO} + X_{CO_2} + X_{N_2} = 1 \quad (18.0)$$

$$X_i = \frac{n_i}{c} \quad (19.0)$$

Where n_i is the molecular density of gas i ; X_i as the molar fraction of the gas; and c is the total number of molecules per unit volume (concentration of the total molecule).

It is assumed that the molar fractions on the electrode surface are in a steady state as long as they do not vary with time. Diffusion through the porous layer, also called the transport problem, is described by the following diffusion equation:

$$\nabla^2 X_{O_2} = \nabla^2 X_{H_2} = \nabla^2 X_{CO} = \nabla^2 X_{CO_2} = \nabla^2 X_{H_2O} = 0 \quad (20.0)$$

Through the Fick's Law, one can calculate the N_X flow of the various exhaust gases X through the porous layer:

$$N_{O_2} = -\frac{cD_{O_2}}{\tau} \nabla X_{O_2}, \quad (21a)$$

$$N_{CO_2} = -\frac{cD_{CO_2}}{\tau} \nabla X_{CO_2}, \quad (21b)$$

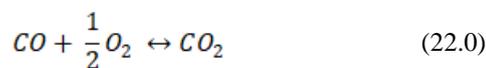
$$N_{H_2} = -\frac{cD_{H_2}}{\tau} \nabla X_{H_2}, \quad (21c)$$

$$N_{H_2O} = -\frac{cD_{H_2O}}{\tau} \nabla X_{H_2O}, \quad (21d)$$

$$N_{CO} = -\frac{cD_{CO}}{\tau} \nabla X_{CO}. \quad (21e)$$

The diffusion coefficient D_i of the various components i of gases depends on the shape of the molecules and the physical properties of the porous layer, such as tortuosity (τ) and width (l).

To understand how the lambda probe works, it is assumed that the exhaust gases contain only four types of gases: O_2 , CO , CO_2 e N_2 . Assuming that nitrogen is inert, platinum catalyzes the reaction:



The molar fraction of each species depends on the air and fuel ratio provided by the engine. This relationship is parameterized by λ , an amount selected so that, for this model, the oxygen concentration is half the carbon monoxide concentration occurring at $\lambda = 1$.

The partial differential equations that describe the various concentrations of gases in the porous ceramic layer of the probe:

$$\frac{\partial(cX_i)}{\partial t} = -\frac{\partial N_i}{\partial x} \quad (23.0)$$

Where X_i is the molar fraction of the total gas concentration for each species I , N_i [mol/cm²s] is the molar flow and c [mol/cm³] is the total concentration of all gas species. Fick's Law of chemical diffusion establishes that in situations where the chemical species in diffusion are not affected by the others, the N_i flux is proportional to the gradient for the molar concentration:

$$N_i = -\frac{D_i}{\tau} \cdot \frac{\partial(cX_i)}{\partial x} \quad (24.0)$$

Where D_i [cm²/s] is the chemical diffusibility of gas i and τ is the tortuosity of the pores of the ceramic layer. In this way, a diffusion equation system is obtained:

$$\frac{\partial(X_i)}{\partial t} = \frac{\partial}{\partial x} \left(\frac{D_i}{\tau} \cdot \frac{\partial(X_i)}{\partial x} \right) \quad (25.0)$$

A solution is sought for the differential equations in steady state. For the one-dimensional model, N_i and c are assumed to be constant in this way:

$$\frac{\partial X_i}{\partial x} = \text{constante} \quad (26.0)$$

In the platinum electrode, it is assumed that, at steady state, the rate at which CO_2 , CO , and O_2 are being created and destroyed must be balanced by the inlet flows of these types of gases. This is,

$$\begin{aligned} r \left(K_I \sqrt{p} X_{CO} X_{O_2}^{\frac{1}{2}} - X_{CO_2} \right) &= \frac{cD_{CO_2}}{\tau} \cdot \frac{\partial X_{CO_2}}{\partial x} \\ r \left(K_I \sqrt{p} X_{CO} X_{O_2}^{\frac{1}{2}} - X_{CO_2} \right) &= -\frac{cD_{CO}}{\tau} \cdot \frac{\partial X_{CO}}{\partial x} \\ \frac{r}{2} \left(K_I \sqrt{p} X_{CO} X_{O_2}^{\frac{1}{2}} - X_{CO_2} \right) &= -\frac{cD_{O_2}}{\tau} \cdot \frac{\partial X_{O_2}}{\partial x} \end{aligned} \quad (27.0)$$

To obtain the boundary conditions for the equation describing the diffusion of the types of gases through the porous layer, note that equation 27 leads to:

$$\begin{aligned} D_{CO_2} \frac{\partial X_{CO_2}}{\partial x} &= -D_{CO} \frac{\partial X_{CO}}{\partial x} \\ D_{CO_2} \frac{\partial X_{CO_2}}{\partial x} &= -2D_{O_2} \frac{\partial X_{O_2}}{\partial x} \end{aligned} \quad (28.0)$$

As [18] it is possible to work at an operating point, neglecting parameters whose derivative is constant. Thus, the simplified lambda probe model can be described in the equation below as:

$$X_{O_2}^{exh} = \frac{1}{2} X_{CO}^{exh} \quad (29.0)$$

Therefore, when stoichiometry occurs, in $\lambda = 1$, as shown in Figure 2, the stoichiometric oxygen exchange occurs at $\lambda = 0,999433$, generating a potential difference in the sensor electrodes, shown in Figure 3.

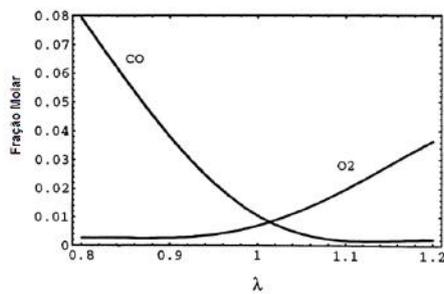


Fig.2 - Molar fractions of exhaust gases. Source: [18]

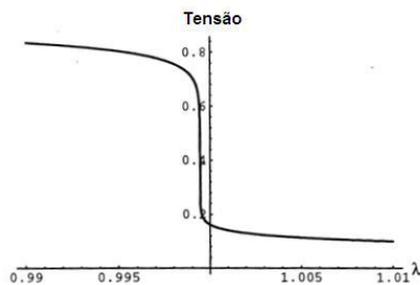


Fig.3 - Voltage through the oxygen sensor for the simplified model of Fick's Law. Source: [18].

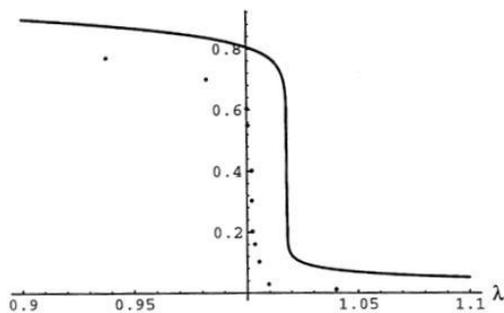


Fig.4 - Asymptotic voltage as a function of λ . Source: [18].

Based on Figure 4, for Oxygen, the voltage displayed by the lambda probe if when $\lambda < 1,01197$, the air-fuel mixture rate is said to be rich, since the exhaust gas is more combustible than oxygen, and the voltage generated on the lambda probe it will be approximately 0.9 V, whereas when $\lambda > 1,01197$ the rate is considered poor where the lambda probe voltage will be approximately 0,05 V.

III. EXPERIMENTAL DEVELOPMENT

To preheat the vegetable oil in favorable conditions of complete combustion in a diesel cycle generator, a tank was made, made of stainless steel, that could be coupled to the generator group. The tank is coupled to a 10 HP internal combustion engine for compression testing.

The tank has a coil that runs through it, shown in figure 5.0. It has an internal diameter of 35.40 mm and an external diameter of 38.51 mm, shown in figures 6.0 and 7.0, through which the exhaust gases will pass and a resistance of 3 kW figure 8.0, which will initially heat the oil, coupled in the part center of the tank.



Fig.5 - Serpentine through which the exhaust gas passes.



Fig.6 - Exhaust gas tube internal diameter.



Fig.7.0 - Outside diameter of the exhaust gas pipe.



Fig.8- Electrical Resistance 3 kW

The heating tank has external dimensions of 258.54 mm high, 102.39 mm wide, and 550 mm long, figure 9.0.



Fig.9- Heating tank overview

The oil viscosity control variables are identified by thermal and oxygen sensors. The thermal sensors for this case are the thermocouple sensors type J and K and the oxygen sensor will be the lambda probe.

The function of the thermal sensors is precisely to act as a thermometer for vegetable oil (sensor type J) and for exhaust gases (sensor type K), indicating to the controller if the oil is at the appropriate temperature in which it is assumed that in that interval, the oil will show kinematic viscosity similar to that of diesel oil. And what is the temperature of the exhaust gases to control the opening of the valve that controls the gas flow in the coil that exchanges heat with oil, so that, according to the physical properties, the conducted heat is sufficient for the oil to maintain its temperature as close as possible to the reference temperature.

The type J thermocouple sensor was chosen to measure the temperature of the vegetable oil in the heating tank, as its use is recommended for temperatures ranging from -200 to 790°C and as it is desired that the oil reaches temperatures between 80°C and 120°C , the reduced scale and close to the desired values reduces the percentage of measurement error. Furthermore, the J-type thermocouple is composed of iron, copper, and nickel and as it is difficult to obtain iron wires with high purity content, the J-type becomes cheaper.

The type K sensor operates between -200°C and 1200°C , having a sensitivity of approximately $41\mu\text{V}/^{\circ}\text{C}$.

The lambda probe is also used to control the viscosity of the oil because it identifies the amount of oxygen in the exhaust gases, this means that the burning of the fuel is incomplete, therefore, the ratio of the air and fuel mixture is "poor" and a probable reason is the higher than ideal viscosity of the oil, which would make it difficult to atomize the oil particles with the combustion chamber air. Figure 10.0 shows the Lambda probe installed at the exhaust gas exhaust outlet.

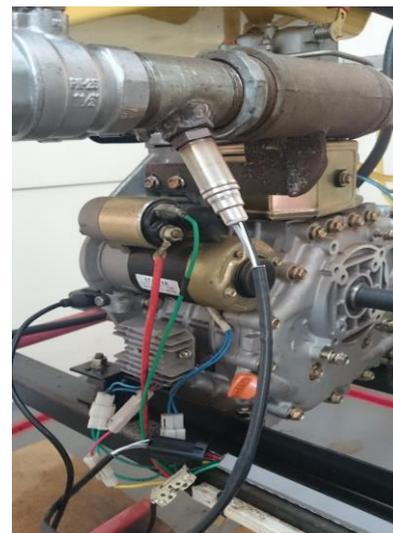


Fig.10- Lambda probe installed at the exhaust gas exhaust outlet.

IV. VISCOSITY CONTROL

For the vegetable oil viscosity control system to work, a data acquisition interface was developed in LabVIEW. Figure 11.0 shows the user interface where the information obtained from the vegetable oil temperature is verified, based on the signals conditioned by the type J thermocouple sensor and the Lambda probe.

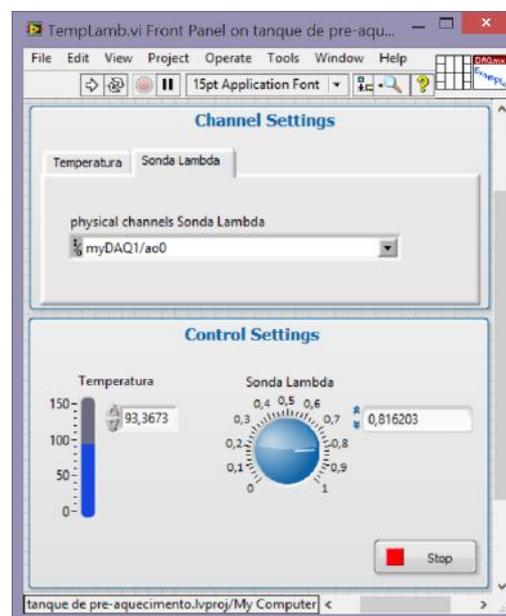


Fig.11 - User Interface.

Figure 12 shows the block diagram of the data acquisition system, the simplicity of the language can be noted, the blocks for configuring the channels and data acquisition can be seen.

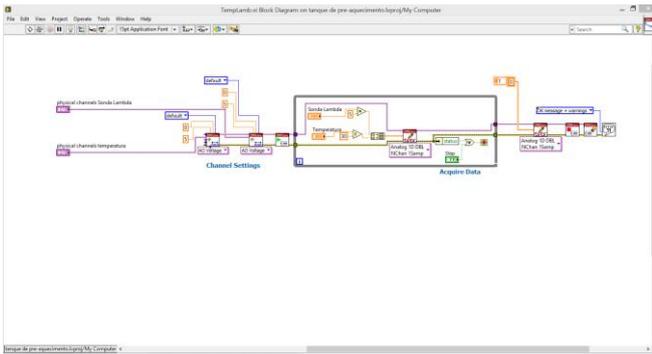


Fig.12- Block diagram of the data acquisition system.

To control the temperature of the vegetable oil heating tank, a controller from National Instrument - NI, MyRio 1900 was used. The purpose of this controller is to activate the internal heating resistance of the tank and the valve to release the exhaust gases from the engine to the internal serpentine of the heating tank. Figure 13 shows the upper and lower limits and the LEDs to activate the outlet valve that releases the exhaust gases to the serpentine inside the heating tank.

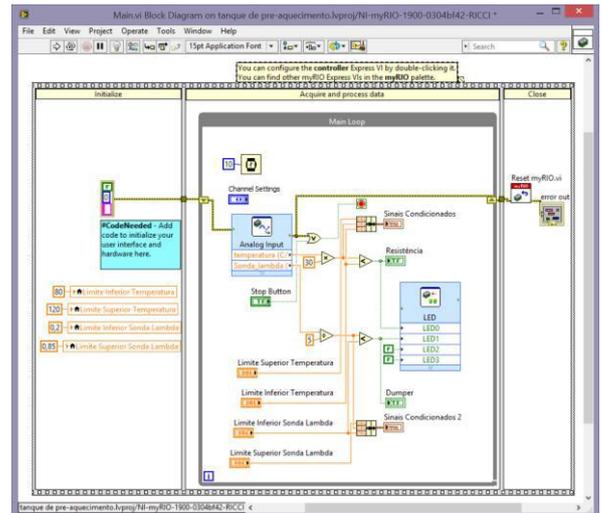


Fig.14- Block diagram of the Controller in real-time of the collected and conditioned signals.

V. CONCLUSION

The use of vegetable oils as a fuel source for the operation of diesel engines is a viable alternative for power generation on isolated communities, where the raw material can be easily obtained at a low cost. Another incentive to this type of fuel, in addition to generating jobs and income, is to promote a better life quality to the community.

On the environmental side the use of vegetable oil in engines results on the reduction of greenhouse effect gases emissions and on the recovery of degraded areas by reforestation with oilseed species, containing the erosion and making a better carbon balance. The vegetable oil viscosity was an impeditive factor for this application, however, this article demonstrated that it is possible to use vegetable oil as a fuel, reducing its viscosity through the complete burning control and the heating tank temperature control.

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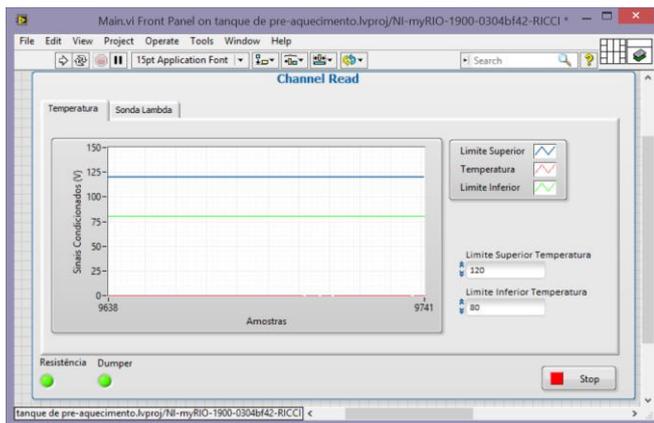


Fig.13- Upper and lower limits of the oil temperature in the tank.

Figure 14.0 is the block diagram of the controller in real-time of the signals collected and conditioned by the data acquisition system. The controller makes decisions based on the logic between temperature and lambda probe.

This system composed of sensors, controllers, and data acquisition allows the control of the viscosity of vegetable oil by means of temperature, through an innovative process using the lambda probe as a burning parameter.

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