Perspectives for biobutanol blends used in small scale cogeneration plants

N. Lontis, T. Gavrilă Tordai, I. Ionel, F. Popescu

***Abstract*—** Reducing the fossil fuel consumption is the major debate of nowadays governments. Each liter, gallon or tone of fossil fuel is worth saving. Less fossil fuel used in the industry transfers to less pollution impact on the environment. One way to produce energy and save fossil fuel consumption is cogeneration with reciprocating internal combustion engine. The most efficient reciprocating internal combustion engine in converting fossil fuel into energy is the diesel engine. One major advantage of the diesel engine is that it can be operated with other unconventional fuels, based on oleaginous plants. Another aspect that must be highlighted is that, the diesel engine can operate with blends of conventional fuel and bio fuels. The paper's approach is cogeneration with biofuel, thus highlighting even more the benefits of the solution proposed in reducing fossil fuel consumption. The biofuel used to operate the internal combustion engine is made by a blend of biobutanol and diesel in volume parts. Studies regarding the efficiency, environmental pollution.

***Keywords*—**biobutanol, environment protection, reciprocating, internal combustion engine, profitability.

I. Introduction

THERE is a constant search of the owners of commercial buildings and commercial businesses to use energy more efficiently. This is a direct result of dramatically increasing electric rates, decreased power reliability (blackouts, brownouts, rolling blackouts, and other power interruptions), as well as competitive and economic pressures to cut expenses, increase air quality, and reduce emissions of air pollutants and greenhouse gases. The present paper analyzes the possibility of using alternative fuels in a small scale cogeneration plant, outlining in a comparison study, the behavior of the cogeneration block when the primary energy source (fossil fuel) is replaced with bio-fuel, presenting the advantages from the energetic and environmental point of view [1], [3].

One major concern of today's environmentalists is the reduction of CO_2 emissions. CO_2 translates into reduction of the fuel consumption [2], [12]. A solution to reduce fuel consumption, when electric energy and heat is produced in cogeneration, is by using internal combustion engines as primary movers. The most common reciprocating internal combustion engines used in cogeneration systems, that have bigger advantages then other engines are diesel engines [4]. The major advantage of the diesel engine is that it can be fired with other fuels then fossil like rapeseed oil, blends of rapeseed oil and fossil, biodiesel [5], [6]. The novelty of this research is that the primary fuel of used in operating the small scale cogeneration plant was a blend of biobutanol and fossil fuel(diesel) mixed by volume parts. Biobutanol ($C_4H_{10}O$) is an alcohol produced trough anaerobe fermentation that has a high calorific value compared with other alcohols. The energy content of biobutanol 33.1 Mj/kg, close up to the gasoline and a density of 0.810 kg/l [7], [8], [9], [10]. A density close to the diesel uel, biobutaol can easily make a homogenous mixture, encouraging the use of this fuel in cogeneration plants [14], [15], [16], [21], [22]. It remains to see what other advantages and disadvantages are highlighted when results are presented.

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II. Experimental Facility

In the Multifunctional Laboratory of Thermal Machines and Unconventional Energies of the "POLITEHNICA' University from Timisoara, the pilot cogeneration plant that represents the experimental facility was build. The development of the of the pilot cogeneration plant had a background regarding the replacement of conventional fuel with the biobutanol blends. From the beginning, the primary mover of the small cogeneration plant was preferred a reciprocating diesel internal combustion engine, due to its multiple advantages regarding the thermodynamic behavior. Taking into consideration the overall dimensions and allocated space inside the laboratory, a compact solution was chosen. An air cooled reciprocating diesel internal combustion engine, with one cylinder, 406 cc, and maximum power of 5.5 kW at 3000 rpm. The electric generation that provides power is coupled directly on the main shaft of the engine, without any gears, forming in this way a compact solution.

The second component of the cogeneration plant (thermal energy source), war developed accordance with to the space constraint and the nature of the hot flue gas. Due to the corrosive action and high temperatures of the flue gases, the thermal energy unit (heat exchanger) was build from stainless steal. In order to recover the highest amount of heat from the hot flue gases, the heat exchanger was mounted into a divergent convergent nozzle, coupled at the exhaust of the reciprocating internal combustion engine.

In figure one it is resented the assembly of the experimental facility at the "POLITEHNICA" University from Timisoara.

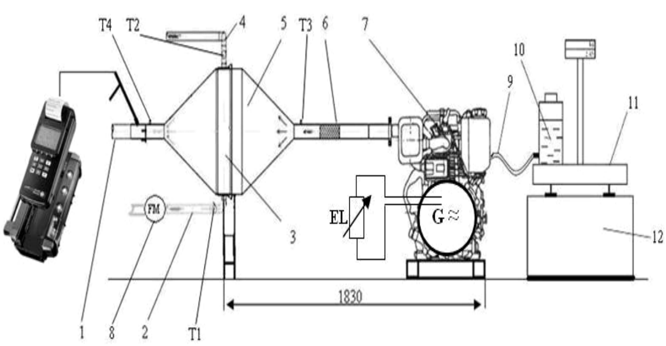


Fig. 1 Experimental facility

1-Exhaust gas outlet, 2-Water inlet (cold), 3-Heat exchanger, 4-Water outlet (warm), 5-Nozzle, 6-Engine vibration absorber, 7-Diesel engine, 8-Water flow meter, 9-Fuel pipe, 10-Additional fuel tank, 11-Electronic weightier, 12-Weightier frame, G-electric generator, 13-Electric load, T1,T2-Thermocouples for thermal agent, T3,T4-Thermocouples for flue gases.

Evaluating the pilot cogeneration plant from the efficiency and environmental point of view, it is mandatory to monitor the system with sensors that have high precision. To rank the first component of the energy's produced by the cogeneration facility, it is necessary to determine the temperature of the flue gases and working medium passed through heat exchanger. For this operation a data acquisition system was developed. The system includes thermocouples, analogical digital converters, data acquisition board and software. In order to monitor the temperature of the hot flue gases at the inlet and outlet of the heat exchanger, thermocouples K-Type ware used (T3, T4 – Fig.1). The same type of thermocouples ware used to monitor the temperature of the working medium at the inlet and outlet of the heat exchanger (T1, T2 – Fig.1).

The data acquisition system developed for this application was adopted from National Instruments. The product used for the pilot cogeneration plant in the matter of DAQ Board was the E-series PCI 6224, that can read samples up to 250 per second. Due to the fact that the National Instruments products have the highest precision in the range of 0 – 10V analog input, it was required to connect the thermocouples to analogical digital converters, and after that the signal introduced into the DAQ Board. The Pixsysy ATR 243 ABC digital analogical converters war acquired and connected with the thermocouples from the experimental facility. The liberalized signal processed by the converters was transmitted then to the DAQ Board.

To be able to store the data from the acquisition system, software was developed in LabVIEW 8.5. The major advantage of this programming environment is that uses virtual instruments and a friendly graphic human interface. The logic used in developing the software was attested also in other scientific publications [7], [8], [9], [11], [13].

Regarding the environmental pollution evaluation, the flue gases war analyzed by a flue gas analyzer TESTO 350 M/XL that measure concentration using standardized methods. This device is part of the LaCIEDiN Measurement Laboratory, attested by the Romanian Accreditation Association National Association Body within the "POLITEHNICA" University from Timisoara Faculty of Mechanics, and is calibrated annually by the National Institute of Metrology. The device analyzed the evolution of the nitrous oxides and dioxide, when initial parameters of the experimental facility have been modified.

To be able to evaluate the pilot cogeneration plant developed, it is mandatory to determine the energy input, and the energy output resulted trough thermodynamic processes. The energy content of the fuels was measured gravimetrically with a digital weightier. The fuel (blends) weight was monitored continuously during the tests, calculating in this way the energy introduced in the pilot cogeneration plant.

The energy recovered from the flue gases trough the heat exchanger, was determined by monitoring the flow of the thermal agent (water in our case). The device used is a stat of the art flow measurement system, which uses ultrasonic waves in calculation the flow. This device was connected also to the DAQ Board, acquiring in the same time with the temperature the flow of the thermal agent.

To simulate the loading steps, a variable electrical resistance was connected to the electric generator. The variable electric resistance can be switched at different values from 1 kW up to 5 kW, simulation in this way the electric load.

It must be not overlooked that the highest efficiency of a cogeneration plant it reached when the facility is submitted at the maximum load. On the other hand the power demand and the thermal demand vary. In this consideration ware developed several loads for the pilot cogeneration plan in cause.

Based on the assumptions previously created, for the pilot in cause was created a measurement plan as follows:

- To be able to present a curve regarding the efficiency of the cogeneration system, three loading steps ware developed till maximum loading point is reached. First loading step was set at 2 kW, second at 4 kW and third at 5.5 kW.
- The second input parameter that was modified during the study was the biofuel created by bending biobutanol and diesel by volume parts. In establishing the concentrations of biobutaol in diesel by volume parts, the technical specification of the primary mover provided by the manufacturer ware consulted. In this way ware developed four fuels: 2% biobutanol and rest diesel, 5% biobutanol and the rest diesel, 7% biobutanol and rest diesel and 10% biobutanol and rest diesel.
- The pilot was tested during 5 hours times for each fuel type and each loading step.
- To further strengthen the research results, the saving data time factor was set at 10 seconds, enabling the data

acquisition system to present for each thermodynamic parameter a value every 10 s.

III. Results and discussions

The first step of the step of the comparison study was in establishing the reference values. The comparison values are determined by running the pilot cogeneration plant with fossil fuel (diesel). Based on the value obtained from the data acquisition system, energy content of the fuel and thermal agent flow, the total efficiency of the cogeneration plant was calculated. The results are presented for each loading step in Fig. 2, highlighting the two forms of energy.

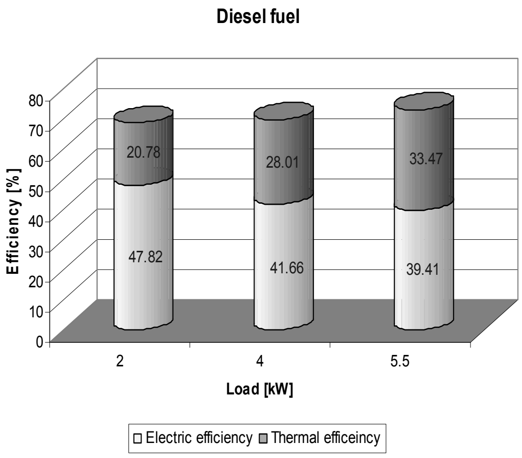


Fig.2 Efficiency of the cogeneration plant, when diesel is used as primary fuel

A first conclusion is emerging from these preliminary results. The electric component of the efficiency remains almost the same for all the loading steps, only the thermal component is changing. This is causes by the temperature of the flue gases, which is rising when the load of the thermal engine is increased.

In parallel with the measurement made for the temperatures and flows, emissions ware monitored. In Fig. 3 it is presented the values obtained for CO_2 emission, when the electrical loading steps ware applied to the cogeneration plant, and diesel fuel was used as primary fuel.

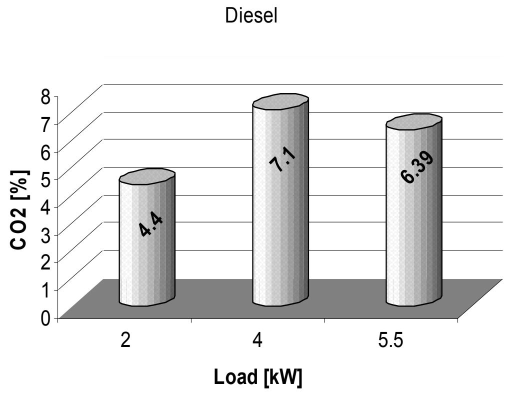


Fig.3 CO_2 values obtained when diesel is used primary fuel

A small observation can be pointed out that for the 4 kW loading step, the value of the CO_2 has the maximum peak.

Another focus of the study, regarding the environmental impact is the emission of NO_x. In Fig. 4 are presents the values of the obtained when diesel was used ay fuel. The flue gas analyzer monitors the pollutant species in ppm. According to the legislation, these values must be related to the reference oxygen. Due to the fact that the pilot cogeneration plant has the primary mover a reciprocating internal combustion diesel engine, the value of the reference oxygen is 3%, so the values are expressed in [mg/m^3], related with the 3% reference oxygen.

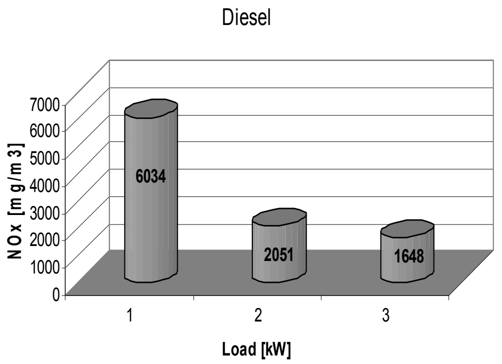


Fig. 4 NO_x values obtained when it was used as primary fuel diesel

After the reference values ware established, the research was advanced the second phase, monitoring the behavior of the cogeneration plant, by replacing the primary fuel with blends of biobutanol and conventional fuel by volume parts. The same measurement and simulation conditions ware also used in order to obtain a comparison study.

a. Primary fuel 2% biobutanol-98% diesel

Fig. 5 presents the values obtained for the efficiency of the cogeneration block, when the primary fuel was replaced by 2 % biobutanol blend with diesel.

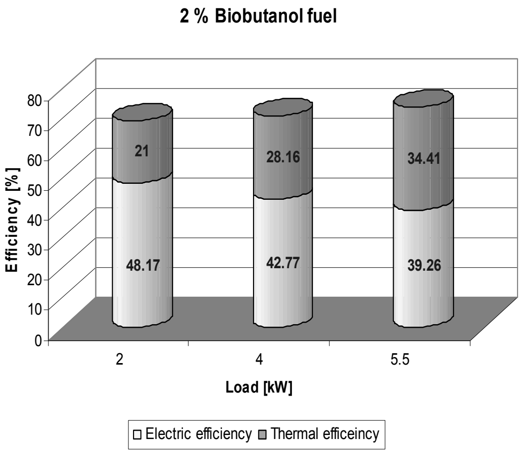


Fig. 5 Efficiency of the cogeneration plant when, 2 % biobutanol blend is used as primary fuel

To highlight even better the differences obtained for the situations created, in Fig.2 and Fig.5 the efficiency values are presented separately for each type of energy. From the efficiency point of view the new fuel created by blending 2% biobutanol in diesel by volume parts brought benefits, in average with 1 %, regarding the efficiency. The 1 % increase it is gained from the thermal efficiency. This is translated to the increased temperature of the flue gases.

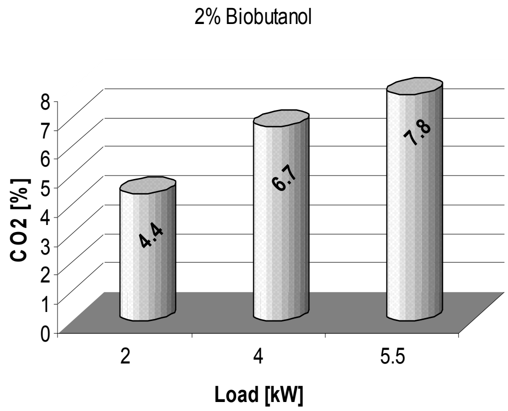


Fig. 6 CO_2 values obtained when 2% biobutanol blend is used primary fuel

The same increase with 1%, is attested also for the CO_2 emission for and 5.5 kW. In comparison with the reference values a slight difference in decreasing is experienced at the 4 kW.

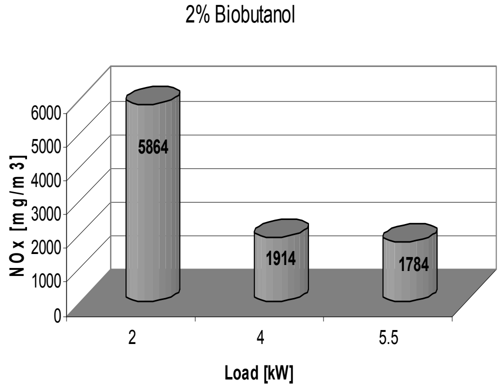


Fig. 7 NO_x values obtained when it was used as primary fuel 2%, biobutanol blend

The values presented in Fig.7 prove that at the load of 2 kW the emission is decreasing, the same trend is recorded also for the 4 kW electric loading step. At the load of 5.5 kW the emission is increasing. This behavior is attributed to the intensification of the temperatures inside the reciprocating internal combustion engine. This behavior was attested in other works [17], [19], [21], [22].

- *b. Primary fuel: 5% biobutanol-95% diesel*

The results for the efficiency, divided by energy form are presented in Fig.8

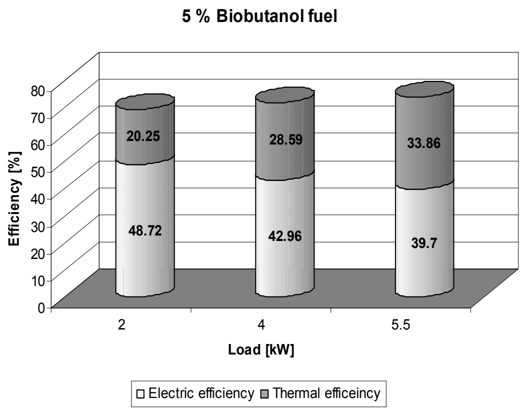


Fig. 8 Efficiency of the cogeneration plant when, 5 % biobutanol blend is used as primary fuel

In comparison with the reference values for all electrical loading steps applied to the pilot cogeneration plant it is experienced an increase around 1 %.

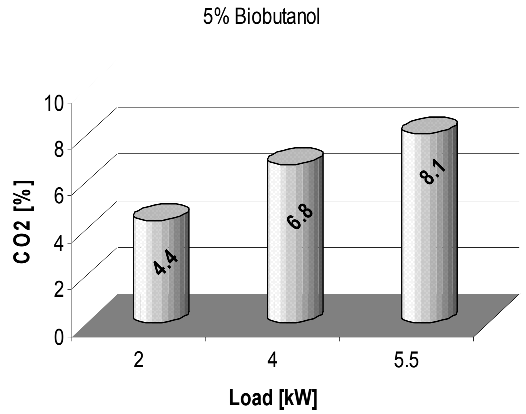


Fig.9 CO_2 values obtained when 5% biobutanol blend is used as primary fuel

The results presented in Fig.9 for the CO_2 emission reveals an increase of almost 2% CO_2. The reason for the CO_2 increase the intensification of the burning process inside the reciprocating internal combustion engine merged with the fact that the biobutanol fuel has an extra oxygen molecule, that is single chemical bound to the rest of formula, therefore it is not necessary a big amount of energy to break the chemical bond of the oxygen molecule. The free molecule the can easily combine with the carbon resulted during the burning process forming extra CO_2.

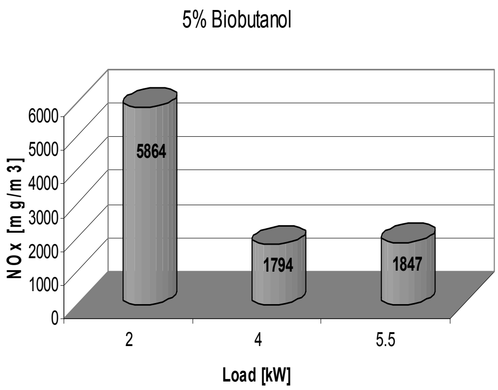


Fig. 10 NO_x values obtained when it was used as primary fuel, 5% biobutanol blend

The level of the NO_x emission on each loading step presents modifications. For the 2 kW loading step the emission is lower compared to the reference values recorded. The trend for the second electrical step (4 kW) regarding the NO_x emission is descending. The 5.5 kW loading step, presents a higher emission value then the reference value and the one obtained when 2% of conventional fuel was replaced with biofuel.

Increasing the temperature inside the combustion chamber of the g internal combustion engine, will help forming more NO_x. The emission is increasing even more due to the fact that the free molecules of oxygen are hurry in making chemical equilibrium. This aspect must be further studied to see the evolution.

- c. *Primary fuel: 7% biobutanol- 93% diesel*

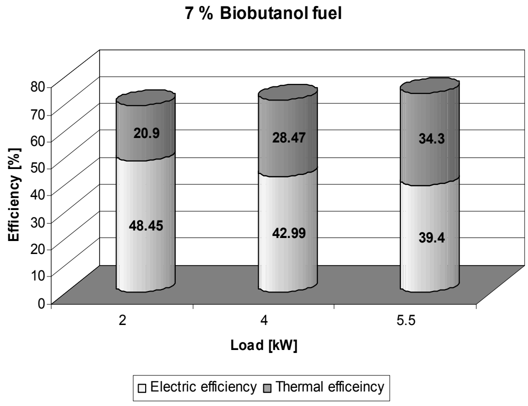


Fig. 11 Efficiency of the cogeneration plant when, 7 % biobutanol blend is used as primary fuel

Fig. 11 presents the efficiency of the cogeneration plant, when 7% of fossil fuel is replaced by biofuel. The values experienced in this case are in the same trend as the situation b. 5 % biobutanol and the rest diesel and situation a. 2 % biobutanol and the rest diesel. They are increasing around 1 %, in comparison with the reference values.

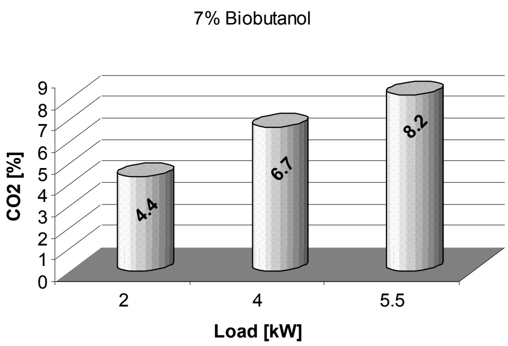


Fig.12 CO_2 values obtained when 7% biobutanol blend is used as primary fuel

For the CO_2 this step presented a slight increase only at 5.5 kW electrical loading step, in comparison with the reference values, and the ones recorded for the previous situations. The increasing is guided by the nature of the biofuel and the thermodynamic processes inside the primary mover.

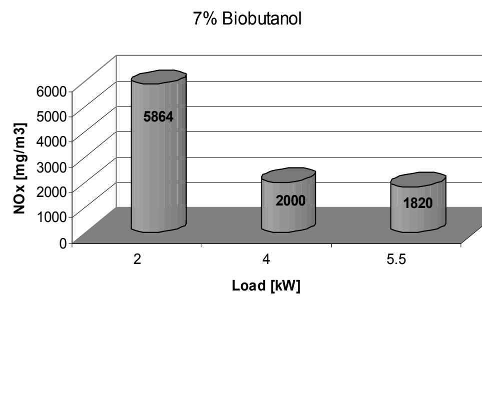


Fig. 13 NO_x values obtained when it was used as primary fuel, 7% biobutanol blend

For the first time it is experienced an increase of the NO_x emission not only at the last electrical loading step but also at 4 kW, and the increase is significant. This behavior was expected due to the fact that by increasing the biobutanol concentration in diesel automatically will be born free oxygen molecules willing to combine with molecules of nitrogen.

- d. *Primary fuel: 10% biobutanol- 90% diesel*

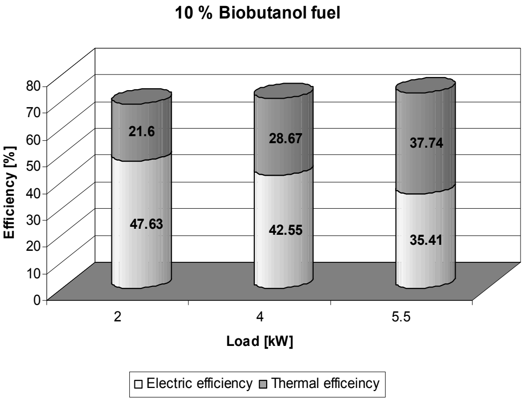
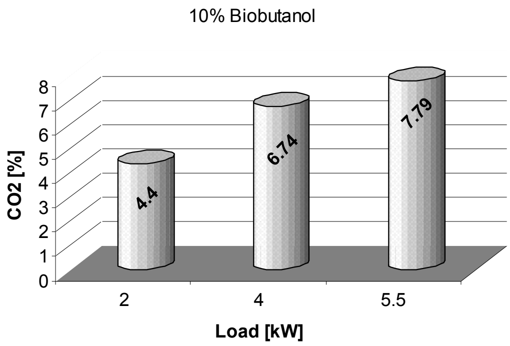


Fig. 14 Efficiency of the cogeneration plant when, 10 % biobutanol blend is used as primary fuel

Fig. 14 presents the total efficiency obtained when the maximum biobutanol blend in diesel was reached. In comparison with the reference values, the trend of the efficiency in this case is upward.



The trend of the CO_2 emission at the maximum biobutanol blend is upward compared to the reference values, for the 5.5 kW electrical loading step, and decreasing for the 4 kW loading step.

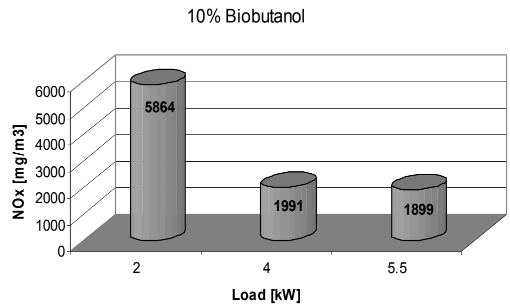


Fig. 16 NO_x values obtained when it was used as primary fuel, 10% biobutanol blend

Figure 16 presents the values obtained for the NO_x emission at 10% biobutanol blend in diesel by volume parts. The value for the electrical loading step of 2 kW remained the same as in the, 2%, 5% and 7% biobutanol blend in diesel. The 4 kW loading step presented a slight decrease of the value in comparison with the value obtained in the case of 7% biobutanol blend in diesel, but increased in comparison with the reference value for the same electrical loading step. It is also recorded that the values of the NO_x emission obtained for the 5 kW electrical loading step is higher that in other cases therefore here the emission has a peak at this concentration. The evolution was also confirmed by other research [19], [22]

IV. CONCLUSIONS

A first conclusion emerges when it comes to cogeneration plant loading. It can be seen that the highest efficiency is obtained when the maximum loading of the pilot cogeneration plant is reached, for all situation; there fore it is recommended to use the plant at the maximum load supported by the primary mover during use. Another revealed aspect is that by increasing the biobutanol concentration in diesel the efficiency increases. This is explained trough the intensification of the combustion mechanics inside the reciprocating internal combustion engine. Due to the chemical composition of the biobutanol, the alternative fuel developed enhances the combustion mechanism. The "free" oxygen molecule from biobutanol formula can easily separate from it, creating a burning support inside the internal combustion engine intensifying this way the combustion.

The advantages obtained regarding the efficiency is in contrast with the increasing of the CO_2 and NO_x emission. The focus on the emissions will be at the maximum loading step, when the highest overall efficiency is obtained. Regarding the CO_2 emission it ca be observed that has a maximum value, when the concentration of biobutanol by volume parts in diesel is 7 %, decreasing when the highest percentage of biobutanol in diesel by volume parts is reached (result are presented in Fig. 17).

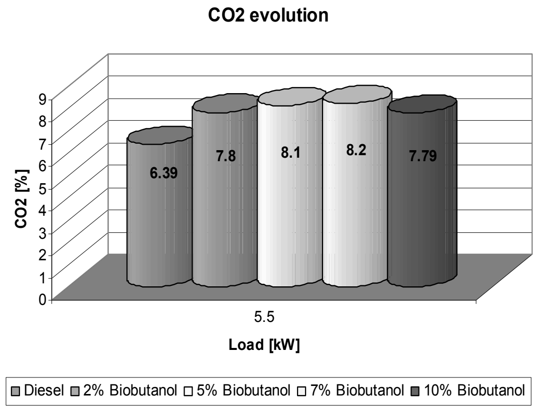
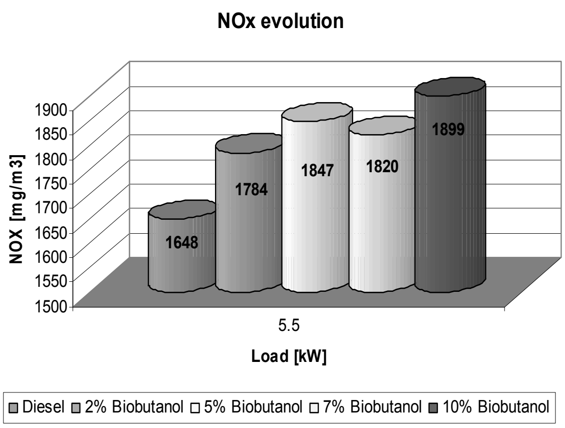


Fig. 17 CO_2 evolution

Another aspect that must be taken into consideration is that biobutanol is a biofuel, and the CO_2 emission from these fuel when is burned is considered to be neutral. Therefore the maximum CO_2 reduction is obtained when it is used as primary fuel the blend of 10% biobutanol-90% diesel Although is higher with 0.6 % in comparison with the reference value obtained, it was managed to replace 10 % of fossil fuel with diesel, gaining more efficiency. Since the biobutanol is produce anaerobic the production costs are smaller from every point of view then for the fossil fuel, making this one worth taking into account. Another aspect that needs to be mentioned is that the biobutanol chemical properties correlate with existing infrastructure to ensure fuel supply logistics, supporting even more a possibility in using biobutaol in blends as alternative fuel.

For the NO_x emission the values are not so encouraging. Fig. 18 presents the evolution of the emission for the maximum load for all the fuels tested.



There is a continuous increase of the emission with the concentration of biobutanol in diesel. This is due to the “free” oxygen molecule from the chemical formula of the biobutanol. At the high temperature developed inside the cylinder of the internal combustion engine the molecule separates from the formula combining very fast with the nitrogen from the air, creating in this way nitrogen oxides. At 10 % concentration of biobutanol in diesel by volume parts, the value obtained for the NO_x emission is at the highest point.

The primary mover initially had another destination, and doesn’t have a catalytic converter. In this way the research must continue mounting on the exhaust trail a three way catalytic converter, reducing the nitrous oxides emissions.

In conclusion using biofuels in small scale cogeneration plants brigns benefits regarding overall efficiency, CO_2 reduction and fossil fuel economy. Regarding NO_x emission behavior when the concentration of biobutanol is increased, there are several aspects that must be restudied.

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Nicolae Lontis, Orsova, December 5 1980, **Mehedinți County, Romania.** "POLTEHNICA" University from Timisoara – Faculty of Mechanics, Dipl. Engineer in Road Vehicle Science, Romania 2004, "POLITEHNICA" University from Timisoara – Master in Ecology in thermal field and transport vehicles, Romania 2005, "POLITEHNICA" University from Timisoara - PhD in Mechanical Engineering in the field of Cogeneration with biofuels, Romania 2008. The major field of study of the author is Cogeneration with biofuels.

After graduation in 2004, he obtains his first job at automotive company. In paralel with his job he followed the master courses at the Faculty of Mechanics from the "POLITEHNICA" University from Timisoara, witch he graduated with success. In 2005 based on his background he obtained a PhD scholarship for three years. In 2008 on 22nd of November he sustained his PhD Thesis with the title Theoretical and experimental research concerning cogeneration with internal engine systems, operating with biofuel at the "POLITEHNICA" University from Timisoara. Since 2008 he is working at the Chair of Mechanical Machines, Technology and Transportation of the Mechanical Engineering Faculty as a Scientific Researcher. As for scientific work below it is presented a small list of representative papers:

- I. Ionel, F. Popescu, N. Lontis , GT Tordai, W. Russ, Co-combustion of fossil fuel with biofuel in small cogeneration systems, between necessity and achievements, 11th WSEAS International Conference on Sustainability in Science Engineering (SSE 09) Timisoara, ROMANIA, MAY 27-29, 2009 WSEAS; "POLITEHNICA" University from Timisoara; Civil Engineering Faculty; ROMANIEN ACADEMY;
- F. Popescu, N. Lontis, I. Ionel, Improving the air quality in urban areas applying cogeneration with biofuels. Case study, Proceedings of the 3rd international conference on energy and development - environment - biomedicine (edeb'09)77-81 2009, Vouliagmeni, Greece, Dec 29-30, 2009.
- I. Vetres, I. Ionel, F. Popescu, N. Lontis, Air pollution analysis in western Romania and the necessity of complementary vertical resolved LIDAR observation, OPTOELECTRONICS AND ADVANCED MATERIALS-RAPID COMMUNICATIONS, Vol. 4 Issue: 8, Pag. 1256-1260, Published: 2010.

Dr. Lontis Nicolae is member of the Balkan Environmental Association.