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THERMO-ECOLOGICAL ANALYSIS OF A GASEOUS-FUEL ENGINE SYSTEM

Master Degree In Renewable Energy and Energy Efficiency

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Dedication

From the deepest part my heart and with the greatest pleasure of this world, I dedicate this work
To my dear father, To my dear mother,
For their sacrifices, their great loves that they bore me.For all they have endured to satisfy all of my concerns in hoping to witness this very distinguished day. May God preserve them in good health and long life and may they find in these modest words the testimony of my gratitude and sincere love.
To my brother Fares and my sister Rihab,
May they be filled with happiness, joy, bliss and fulfillment. I hope my success gives them good courage in their studies, lives... May god preserve them in good health. I dedicate this work to them wishing to them all success and proving that we are only separated by distance, joined by love.
To all the members of my big family Receive here the testimony of my great respect and gratitude, of my gratitude and my deep attachment.
To all my friends
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Abstract

This dissertation presents an ecological assessment of the use of syngas produced from biomass gasification in internal combustion engines. These analyses depend firstly on the environmental impact of the use of syngas in a gaseous-fuel engine, as well as, the ecological performance of the gasification system. Syngas quality is based on conditions parameters such as the equivalence ratio ER, gasification temperature, steam to biomass ratio $STBR$, and surface velocity SV. Also, syngas ecological evaluation depends its ecological criteria such as pollutant indicator π_p, ecological efficiency ϵ. The ecological peformance of the system corresponds to ecological coefficient of performance $ECOP$, effective ecological power density $EFECPOD$.

Results found by applying these analysis are 0.25 for the equivalence ratio, SV varies between [0.82,2.5] m/s. Pollutant indicator is found between [0.015,0.018] kg/MJ which lead to ecological efficiency varies between [96.2,96.7] % . Comparison is conducted between the emission factors and the ecological efficiency achieved by burning the syngas in the internal combustion engine and with those obtained from burning other fuels in a gaseous-fuel engine. Burning syngas has a better environmental impact than burning other fuels such as diesel gasoline or natural gas.

$ECOP$ calculation consists of applying exergetic analysis on system obtaining as a result [0.00931,0.00938] for system 1, and [0.0093,0.0094] for system 2. It highlights the high amount of irreversibilities in the system. $EFECPOD$ is found [87.55,104.17] kW/m^3 for system 1 and [436.26,518.67] for system 2 kW/m^3.

Keywords:
ECOP, EFECPOD, Biomass Gasification, Thermo-Ecological Analysis, Ecological Efficiency.

Resumo

Esta dissertação apresenta uma avaliação ecológica do uso de gás de síntese produzido a partir da gaseificação de biomassa em motores de combustão interna. Essas análises dependem, em primeiro lugar, do impacto ambiental do uso de gás de síntese em um motor a combustível gasoso, bem como do desempenho ecológico do sistema de gaseificação. A qualidade do Syngas é baseada em parâmetros de condições como razão de equivalência ER, temperatura de gaseificação, relação vapor/biomassa $STBR$ e velocidade de superfície SV. Além disso, depende dos critérios ecológicos do gás de síntese, como indicador de poluente π_p, eficiência ecológica ϵ. O desempenho ecológico do sistema corresponde ao coeficiente de desempenho ecológico $ECOP$, densidade de potência ecológica efetiva $EFECPOD$.

Os resultados encontrados pela aplicação dessas análises são 0,25 para a razão de equivalência, SV varia entre [0,82,2,5] m/s, [0,015,0,018] kg/MJ como indicador de poluente que leva à eficiência ecológica varia entre [96,2,96,7] %. A comparação é realizada entre os fatores de emissão e a eficiência ecológica alcançada pela queima do gás de síntese no motor de combustão interna e com aqueles obtidos da queima de outros combustíveis em um motor a gás. A queima de gás de síntese tem um impacto ambiental melhor do que a queima de outros combustíveis, como gasolina diesel ou gás natural.

O cálculo de $ECOP$ consiste na aplicação de análise exergética no sistema obtendo como resultado [0,00931,0,00938] para o sistema 1, e [0,0093,0,0094] para o sistema 2. Ele destaca a elevada quantidade de irreversibilidades no sistema. $EFECPOD$ é encontrado [87,55,104,17] kW/m^3 para o sistema 1 e [436,26,518,67] para sistema 2 kW/m^3.

Palavras-chave:

ECOP, EFECPOD, Análise Ecológica Térmica, Eficiência Ecológica, Gasificação da Biomassa.

Résumé

Cette thèse présente une évaluation écologique de l'utilisation du gaz de synthèse produit à partir de la gazéification de biomasse dans les moteurs à combustion interne. Ces analyses dépendent tout d'abord de l'impact environnemental de l'utilisation du gaz de synthèse dans un moteur à gaz, ainsi que des performances écologiques du système de gazéification. La qualité du gaz de synthèse est basée sur des paramètres de conditions tels que le rapport d'équivalence ER, la température de gazéification, le rapport vapeur/biomasse $STBR$, et la vitesse de surface SV, ainsi que les critères écologiques du gaz de synthèse tels que l'indicateur de polluant π_p, l'efficacité écologique ϵ. La performance écologique du système correspond coefficient de performance écologique $ECOP$, densité de puissance écologique effective $EFECPOD$.

Les résultats obtenus en appliquant ces analyses sont de 0,25 pour le rapport d'équivalence, SV varie entre [0,82,2,5] m/s, [0,015,0,018] kg/MJ comme indicateur de pollution qui conduit à l'efficacité écologique variant entre [96,2 , 96,7] %. Une comparaison est effectuée entre les facteurs d'émission et l'efficacité écologique obtenue en brûlant le gaz de synthèse dans le moteur à combustion interne et avec ceux obtenus en brûlant d'autres carburants dans le moteur à carburant à gas. La combustion de gaz de synthèse a un meilleur impact sur l'environnement que la combust-ion d'autres carburants tels que l'essence diesel ou le gaz naturel.

Le calcul de $ECOP$ consiste à appliquer une analyse exergétique sur le système obtenant comme résultat [0,00931,0,00938] pour le système 1, et [0,0093,0,0094] pour le système 2. Il met en évidence la quantité élevé d'irréversibilités dans le système. $EFECPOD$ est trouvé [87,55,104,17] kW/m^3 pour le système 1 et [436,26,518,67] kW/m^3 pour le system 2.

Mots clés:

$ECOP$, $EFECPOD$, gazéification de la biomasse, analyse thermo-écologique, efficacité écologique

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List of abbreviations

β	Factor dependent upon mass fraction of oxygen, carbon, hydrogen, and nitrogen in the biomass
$\dot{m}$	Mass flow rate
$\dot{n}$	Molar flow rate
$\dot{Q}_L$	Cooling load of the refrigerator
$\dot{v}$	Volume flow rate
$\dot{W}$	Engine Power output
π_p	Pollutant Indicator
h	Enthalpy
I_{ch}	Chemical irreversibility
I_{ph}	Physical irreversibility
P_{ef}	Effective Power
s	Entropy
X_d	Exergy destruction
α	Temperature ratio of the cycle
η_{ef}	Effective efficiency
D_t	Diameter of the throat section of the gasifier
ECOP	Ecological Coefficient of Performance
EE	Effective Efficiency

EFECPOD	Effective Ecological Power Density
EPD	Effective Power Density
ER	Equivalence Ratio
ICE	Internal Combustion engine
JBC	Joule Brayton Cycle
LHV	Low heat value
PM	Particulate Matter
RICE	Reciprocating Internal Combustion engine
STBR	Steam To Biomass Ratio
SV	Surface Velocity

Chapter 1

Introduction

1.1 Objective

The main objective of this thesis is the evaluation of gasification system considering ecological concept. This study aims to investigate the ecological performance of the gasification system. On the other hand, this work presents an evaluation of the environmental impact from the use of syngas and other fuels in internal combustion engines. The performance results will be compared for both systems.

1.2 Thesis Framework

Biomass downdraft reactors, combined with reciprocating internal combustion engines, are a practical innovation for small-scale heat and power generation [1]. For this type of applications, the gasification of biomass in downdraft reactors has been widely studied and is currently considered as a mature technology [2]. An additional advantage of such a rural electrification mechanism is the possibility of using various organic wastes with a considerable reduction in CO_2 emissions. With the awareness of the negative environmental impact caused by the rapid depletion of natural gas and crude oil resources, research and development projects on electricity production with biomass gasification have gained new momentum. In this context, downdraft gasification has the benefit of higher conversion efficiencies with a low rate of tar and particulate matter generation [2]. Natural emissions cover an ever-increasing range of pollutants, hazards and degradation of ecosystems over large areas. The problems of energy supply and energy use are linked to environmental concerns such as air pollution, acid precipitation, depletion of the ozone, and the emission of radioactive substances. These issues must be considered simultaneously in order to achieve a bright energy future with minimal environmental impacts [3].

The widespread availability of biomass has been broadly perceived, as has its potential to supply much bigger sums of valuable energy with fewer natural impacts than fossil fuels [4]. Combustion, pyrolysis and gasification are the three main thermochemical transformation methods to convert biomass into a commercial product. Gasification is admitted as one of the foremost promising advances to change over low-quality powers into more important ones. It has however to solidify its position compared to other procedures for exploiting biomass energy. Gasification could be a thermochemical halfway oxidation process in which carbonaceous substances (biomass, coal, and plastics) are changed over into gas within the nearness of a gasifying operator (air, steam, oxygen, CO_2 or a mixture of these). The gas produced, commonly alluded to as syngas (synthesis gas), comprises basically of H_2, CO, CO_2, N_2, little particles of char (strong carbonaceous buildup), cinders, tars and oils [5]. Today, the global concern is not only focused on the depletion of our energy source, which is petrol, but also on environmental issues and it can be said that this is the main objective. The ecology-based thermo-environmental function is considered to evaluate the performance of the system. This ecological analysis allows determining the environmental impact of any thermal cycle [6].

The syngas production takes place within the gasifier. This produced gas will be used as fuel for an internal combustion engine. The wood is used as the main source of energy to power the gasification system. The syngas will be powering two types of motors which explains that analysis will be applied to two different systems. The first system needs a gasifier, gas/water heat exchanger, wood sawdust filter and RCX-210 engine from the Camperon MRX-50 motor pump. The second system is composed of a gasifier, gas/air heat exchanger, wood sawdust filter and a Honda CG 125 Titan motorcycle engine.

1.3 Structure of the Thesis

The work presented in this thesis is organized into five chapters:

Chapter 1 (Introduction) contains a brief introduction to the present work, and its objectives.

Chapter 2 (Theoretic Foundations) consists of the state of the art in the context of results of some research carried out on biomass gasifiers considering ecological aspects, as well as the theoretical basis of the ecological analyses applied on gasification technology, in addition to the approach of gasification (steps of gasification and types of the gasifier).

Chapter 3 (Material and Methods) presents the materials and methods, with the demonstration of systems and their components.

Chapter 4 (Results and Discussions) presents the results and discussion of the analysis carried out in the two studied systems.

Chapter 5 (Conculsions and Future Work) contains the conclusions of this thesis as well as the possible horizons of the project as a proposal for future work.

Chapter 2

Theoretic Foundations

2.1 State of the Art

Biomass gasification is a thermo chemical process of converting biomass into a mixture of combustible and non-combustible gas. Syngas is a gaseous fuel generated from wood gasification, which can be used as a substitute or complementary fuel in conventional internal combustion engines. Today, the world is not only focusing on finding various solutions to convert energy in an alternative way but also ecological and environmental concern becomes its global priority. Previous studies on gasification process have shown the best compromise between thermal efficiency and ecological impact.

Boloy et al [3] evaluated the environmental impact from the utilization of syngas in internal combustion engines coupled to downdraft gasifier, taking into account technical, economical and ecological aspects. It was found that the system efficiency of the gasifier/ICE achieved values from 13.88% to 15.03%, electrical generation efficiency was around 12.82% and cold gasifier efficiency was approximately 69%. Comparison between the ecological efficiency achieved by burning the syngas in the ICE and ecological efficiencies obtained from burning fossil fuels in the ICE leads to interpret that the burning syngas has a better environmental sustainability than burning fuels such as diesel and B20 biodiesel [3].

Martínez et al reviewed the impacts of the particle size, moisture content of biomass feedstock and the air/fuel equivalence ratio utilized in the gasification process with regard to the quality of the producer gas. Information on the typical performance of various diesel and spark ignition RICEs fed with syngas was presented. This literature indicated that the low heating value and the process cold efficiency for a downdraft type reactor are around 4-6 MJ/Nm3, 50-70%, respectively and the average temperature in the combustion zone is about 1000°C. Results obtained shows that equivalence ratio should be kept between 0.2 and 0.4, the biomass particle size should be less than 5 cm and the moisture content should be less than 25% [2].

Paengjuntuek et al performed an integrated biomass gasification fuel cell system with rice straw feedstock for power generation with the use of Aspen plus 7.2. Optimal operating condition was obtained at 1395.61 kW as electricity production with 69.38% total energy (combined heat and power) efficiency [7].

Lora & Salomon assessed the environmental impacts of thermal power plants in an integral way by using the ecological efficiency parameter. Results allow that environmental impacts of thermal generation are considerably reduced once control methods are implemented [8].

Ruiz et al reviewed gasification techniques and the principle parameters to consider at the design stage of gasification plant. In fact, it has been outlined that temperature, gasifying agent, equivalent ratio, residence time and catalyst additives, such as dolomite and others (which significantly convert the tars, reducing their content in the gases generated) affect the progress of the gasification process as well as the quality of synthesis gas [5].

Susastriawan et al presented a literature review on downdraft gasifiers. They focused on the design parameter and its effect on the performance of the gasifiers and its effect on their performance. They discussed various works on design enhancement of basic model of small-scale downdraft gasifiers [9].

Yasin Ust et al illustrated in their research a proposition of a new performance objective function named ecological coefficient of performance ECOP. This parameter was used as an ecological optimization for an irreversible dual cycle. ECOP was compared to an alternative ecological function defined by Angulo Brown also for the maximum power output condition. Results obtained shows that ECOP max have an advantage over the E_{max} conditions and maximum power output condition in terms of entropy-generation rate as well as in ecological perspective [10].

Also ECOP has been taken as an objective function for the optimization for a generalized irreversible Carnot heat engine in a research made by Üst et al. It is gotten that ideal design parameter at maximum ECOP conditions lead to a higher performance in terms of thermal efficiency and entropy generation rate than at the maximum E conditions [11].

Yasin Ust & Sahin carried out a thermo-ecological performance analysis based on the ECOP criterion for an irreversible refrigerator. They determined the optimal performance and the design parameters by maximizing the ECOP criterion, and also, they discussed the effects of the major irreversibilities on the thermo ecological performances [12].

Caglayn and Caliskan applied thermo ecological analysis of industrial kilns by using ecologic objective function ECO and ecological coefficient of performance ECOP and it was the first study that include these parameters for the industrial kilns. These analyses were tested on the kilns used in the firing process of the ceramic plant. The maximum ECO and ECOP values are determined as 2387.156 kW and 0.051, respectively, while their corresponding minimum values are 2577.394 kW and 0.026, respectively. Optimum working condition with better environmental efficiency were obtained at 10°C [13].

Gonca has performed a thermo-ecological analysis on the gas-mercury turbine system. Exergy destruction and efficiency were determined relying on pressure ratio, air mass rate, and air inlet temperature [2].

Gonca & Sahin applied a new performance analysis criterion called effective ecological power density EFECPOD to a Joule-Brayton cycle (JBC) turbine. The impacts of the turbine design and running parameters on the execution and energy losses of a gas turbine have been numerically examined by using the presented analysis criterion. It is found that the performance parameters such as the effective efficiency (EE), effective power (EP), effective power density (EPD) and effective ecological power density (EFECPOD) increase with pressure ratio, turbine speed, turbine diameter, intake pressure, turbine wall temperature decrease with turbine height, heat transfer coefficient, intake temperature and residual gas fraction [2].

2.2 Ecological Analysis

Gas composition, heating value of the produced gas, yield and the efficiency of the conversion process have such important role towards gas ‘s quality [14]. These performance parameters, depend not only on physical chemical properties of the biomass but also they are influenced by some experimental conditions parameters such as the equivalence ratio ER, reaction temperature, steam to biomass ratio STBR, and surface velocity [15]. Also, gasification process is performed from an ecological point of view. That is why, some parameters are analyzed to investigate the environmental impact of the produced gas such as ecological coefficient of performance ECOP, pollutant indicator π_p, ecological efficiency, effective ecological power density EFECPOD.

2.2.1 Equivalence Ratio

ER is one of the foremost critical parameters, which have impact on the gasification process counting syngas composition. Therefore, it is considered as an important parameter which influences the gasification efficiency. ER is the ratio of the real air/fuel proportion to the stochiometric air/fuel proportion [16]. It is also defined as the quotient of the actual air volume supplied per kg of biomass fuel and the volume of the gasification agent which is mostly air due to its availability and cost consideration [5]. This parameter shows the concentration of tar content during gasification. High ER implies better oxygen content allowed to react with the volatiles present in the combustion zone. As long as ER is increasing tar formation in the product gas is reduced [17]. Typically, ER is 1 for the perfect combustion and range between 0.2 and 0.4 in biomass gasification [9]. When the raw gas is going to be burned in downstream furnaces, without being cooled first, the gasifier can operate at minimum ER (around 0.20) because the gas must have the maximum possible calorific value [18]. ER is defined as follows:

$$ER = \frac{\dot{m}_{air}}{\dot{m}_{air,stoic}} \tag{2.1}$$

Where, $\dot{m}_{air}$ is the mass flow rate of air and $\dot{m}_{air,stoic}$ is the mass flow rate of air required for stoichiometric combustion. It is also presented as follows [5]:

$$ER = \frac{r_{(air-fuel)real}}{r_{(air-fuel)stoic}} \tag{2.2}$$

Where, $r_{(air-fuel)real}$ the air–fuel ratio for the current is process and $r_{(air-fuel)stoic}$ is the air–fuel ratio for complete combustion.

2.2.2 Steam to Biomass Ratio STBR

Just like the equivalence ratio ER, steam to biomass ratio STBR is one of the main parameters that refer to the amount of gasifying agents affecting the performances of gasifier [19]. It is predicted that when the steam to biomass proportion increases, the H_2 mole fraction increases and the sum of CO and CH_4 diminishes. Therefore, at higher steam/biomass ratio, the hydrogen yield increases to a high extent [20].

$$STBR = \frac{\dot{m}_{air} + \dot{m}_{bio,moisture}}{\dot{m}_{bio,d.b.}} \tag{2.3}$$

Where $\dot{m}_{air}$ steam is the mass flow rate of the steam, $\dot{m}_{bio,moisture}$ is the mass flow rate of the moisture in biomass and $\dot{m}_{bio,d.b.}$ is the mass flow rate of the dry biomass

The present work analyses the syngas gained from a gasification process in which the air is the gasification agent. STBR is a parameter that has to be affected only to steam gasification which is not this work's case.

2.2.3 Gasification temperature

Syngas composition depends to a great extent on temperature in gasifier bed as well. Temperature has an impact on the carbon transformation all through the oxidation and gasification reactions, gas yield, heating value, cold gas effectiveness and at long last char and tar yields in gasification processes as well [16]. Gasification temperature can be influenced by equivalence ratio. The temperature increases as expanding equivalence ratio due to upgrading combustion reaction in oxidation zone [9]. Franco et al mentioned that the increase in temperature led to higher gas yields with a decrease in the amounts of coal and liquids formed. It may be due to advance breaking of the fluids and increased reaction of the coal with the gasification medium [15].

2.2.4 Surface velocity

Surface velocity SV is characterized as the ratio of the syngas production rate at ordinary conditions and the tightest cross sectional range of the gasifier [2]. SV is considered as the most important measure of gasifier performance because it controls gas production rate, fuel consumption rate, gas energy content, char and tar production rate. It allows a direct comparison of gasifiers with different power outputs because it is independent of reactor dimensions. In fact Yamazaki et al detailed a case with a great execution of the gasifier when a low tar substance in producer gas and high effectiveness were gotten for SV values of approximately 0.4 m/s. Low values of SV result in a generally moderate pyrolysis handle with high yields of char and critical amounts of unburned tars. In any case, such high SV values may essentially diminish the gas residence time in the gasifier, coming about in lower efficiencies within the tar cracking process [10].

SV is expressed as follows:

$$SV = \frac{\dot{V}_{syngas}}{S} \tag{2.4}$$

Where $\dot{V}_{syngas}$ the volume flow rate of the produced gas, and S is the tightest cross sectional range of the gasifier.

2.2.5 Syngas Composition

The syngas produced through the gasification process consists mainly of hydrogen (H_2) and carbon monoxide (CO) and inert gas such as nitrogen (N_2), and carbon dioxide (CO_2). The main characteristics of the syngas fuel are the lower heating value, the H_2/CO ratio. For syngas fuels combustion, the effect of hydrogen content is very important. The replacement of methane with syngas with high hydrogen content will help to reduce the CO_2 emissions. Table 2.1 present the syngas properties at 673K [21].

Table 2.1: Syngas properties at 673K

Gas	Mass (%)
CO_2	15.10
CO	16.70
H_2	01.70
N_2	63.30
Sum	96.8

This syngas is used as fuel in the engine. The chemical reactions that took place in the engine are expressed as follows:

$$CO + \frac{1}{2}O_2 \rightarrow CO_2 \tag{2.5}$$

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \tag{2.6}$$

As [22], air-syngas stoichiometric ratio is 1.2.

2.2.6 Ecological coefficient of performance ECOP

As mentioned in section 2.1, another innovative ecological analysis was proposed in a study made by Y. Ust, B. Sahin, and A. Kodal [23] where they proposed a new performance objective function named ecological coefficient of performance ECOP [23]. The ecological coefficient of performance is introduced as the work-energy per unit loss rate of availability. This new parameter was defined that is dimensionless and always has positives values just like the coefficient of performance in heat pumps or thermal efficiency in heat engines [23]. The presented ECOP gives the data for the rate of the entropy generation or rate of the availability loss [24]. It is worth to mention that the entropy generation is minimized when the ECOP is maximized for a certain motor power, refrigerator cooling rate or heat pump heating rate [24]. In fact, it is indicated that optimal design parameter at maximum ECOP conditions lead to a better performance in terms of thermal efficiency and entropy generation rate. The ECOP function offers a tool for evaluating the environmental impact of heat engines. Its higher values show that less entropy is generated for a prescribed amount of power output [25]. It has been considered as an objective function for the optimization. Therefore, ECOP index has an obvious advantage comparing to the E model in term of environmental approach and entropy generation. The point of defining an innovative thermo-ecological optimization process is to achieve the finest conciliation between the work-energy and its waste [24]. In a study made by Gonca, exergy and thermo-ecological performance optimization of a Gas-Mercury combined turbine system were carried out [26]. ECOP was used to examine the combined system. Calculations lead to find this parameter as follows:

$$ECOP = \frac{\dot{W}}{X_d} \tag{2.7}$$

Where X_d the total exergy destruction of the gas-mercury in combined system and $\dot{W}$ is its power output or effective power as mentioned by authors in the original article. Exergy destruction refers to the exergy destroyed due to irreversibilities within a component and it is also called irreversibility which means difference between inlet and outlet exergy.

According to Yasin Ust and Sahin, ECOP for a refrigerator is defined as the ratio of cooling load to the loss rate of availability [12]. It is presented as follows:

$$ECOP = \frac{\dot{Q}_L}{T_0\dot{S}_g} \tag{2.8}$$

Where $\dot{Q}_L$ is the cooling load of the refrigeator, T_0 is the ambient temperature and $\dot{S}_g$ is the entropy generation rate.

ECOP is also proposed by [25] to perform an irreversible brayton heat engine and it is expressed as follows:

$$ECOP = \frac{\dot{W}}{T_0\dot{S}_g} \tag{2.9}$$

2.2.7 Pollutant indicator

In a study made by Cardu and Baica, the notions of Carbon Dioxide Equivalent (CO_{2e}) and Pollution Indicator (π_g) were introduced as two characteristics of the fuel in a thermo power plant [27]. The carbon dioxide equivalent CO_{2e} is composed by a hypothetical pollutant concentration factors. These concentration factors of pollutant such as nitrogen oxides (NO_x) , carbon monoxide (CO), sulphur dioxide (SO_2), particulate matter (PM) is taken into account in environment impact studies of the thermo power plants. For the calculation of this coefficient, the (CO_2) maximum concentration value allowed is divided by the corresponding air quality patterns for (NO_x), (SO_2) and (PM) in hour. Thus, the expression for the (CO_{2e}) is:

$$CO_{2e} = CO_2 + 80SO_2 + 50NO_x + 67MP \tag{2.10}$$

Where, $(SO_2)_e$ = 80 (SO_2) is the sulphuric dioxide equivalent in (CO_2), $(NO_x)_e$ = 50 (NO_x) is the nitrogen oxide equivalent in (CO_2) and the particulate matter equivalent in (CO_2) is $(PM)_e$ = 67 (PM). From an ecological point of view, the best fuel is the one that presents a minimum amount of CO_{2e}, obtained from its combustion. They are expressed in kg/kg fuel, denoted (kg/kgf) [28].

To quantify the environmental impact of the produced gas, pollutant indicator π_p is defined as it follows :

$$\pi_p = \frac{CO_{2e}}{LHV_{syngas}} \tag{2.11}$$

Where, CO_{2e} in kg/kg (kg per kg of fuel), LHV_{syngas} in MJ/kg is the fuel lower calorific power and π_p in kg/MJ is the pollution indicator and kg refers to the mass of CO_{2e} [28].

2.2.8 Ecological efficiency

The ecological efficiency concept depends on the environmental impact caused by CO_2, SO_2, NO_x and particulate material (MP) emissions [3]. This parameter was proposed by [27] just for steam cycles using coal. The use of ecological efficiency was enlarged to combined cycle plants using natural gas, internal combustion engines and conventional and advanced cycles using biomass as fuel [8]. Ecological efficiency is defined as an indicator that makes it possible to assess the performance of thermo-electric power plants. This parameter provides an ecological evaluation by comparing the hypothetically integrated pollutant emission (CO_2 equivalent emissions) to the quality standards of the existing air. Conversion efficiency is also considered a determining factor on specific emissions, expressed as a number of fractions that can be used to determine ecological efficiency.

$$\epsilon = \sqrt{\frac{0.24 \times \eta_{systems} \times ln(135 - \pi_p)}{\eta_{system} + \pi_p}} \tag{2.12}$$

Where ϵ includes, in a single coefficient, the aspects which define the intensity of the environmental impact of the thermoelectric unit, the composition of the fuel, the combustion technology, the pollutant indicator and the thermodynamic efficiency. The parameter ϵ is directly proportional to the efficiency of the thermoelectric plant, inversely proportional to the value of the pollutant indicator π_p, and is also between 0 and 1, similar to the thermoelectric efficiency. The situation is considered unsatisfactory from an ecological point of view when $\epsilon = 0$, while ϵ= 1 indicates an ideal situation from an energy efficiency point of view. According to the fuel classification, pure hydrogen would have 0% impact on the environment, while sulfur would cause 100% impact [3].

2.2.9 Effective ecological power density EFECPOD

Effective ecological power density EFECPOD is a parameter used to evaluate any thermal system‘s performance. It was presented by Gonca and Sahin as a new performance analysis criterion that has been applied to a Joule-Brayton cycle (JBC) turbine [29]. It is defined as follows:

$$EFECPOD = \frac{\eta_{ef} P_{ef}}{\frac{T_1}{T_0} \alpha V} \tag{2.13}$$

Where, α is the temperature ratio of the cycle , η_{ef} is the effective efficiency and they are stated respectively as follows

$$a = \frac{T_{max}}{T_{min}} \tag{2.14}$$

$$\eta_{ef} = \frac{P_{ef}}{\dot{Q}_{syngas}} \tag{2.15}$$

Where, where $\dot{Q}_{Syngas}$ is the total heat from the syngas and it is proposed in the literature as the total heat potential of the injected fuel [29], P_{ef} is the effective power as proposed in the original literature and it is equivalent to the output power of the motor (W) in this study, V is the motor’s volume. T_1 is the inlet temperature of the gas turbine as mentioned in the original study. In this case T_1 is the inlet temperature of gas in the motor. T_0 is the ambient temperature.

2.3 Entropy and exergy fundamentals

2.3.1 Entropy

Entropy is defined as a measure of the amount of molecular disorder within a system. It is also considered as the measure of the thermal energy of a system per unit of temperature that is not available to provide useful work. Based on second law of thermodynamics entropy variations is expressed as follows

$$\partial S = \frac{\partial Q}{T} \tag{2.16}$$

Where, Q refers to the amount of heat transferred in a process and T is the absolute temperature

$$S = S_{ch} + S_{ph} + S_{po} + S_{ki} \tag{2.17}$$

Where, S_{ch} refers to chemical entropy, S_{ph} refers to physical entropy, S_{po} is the potential entropy and S_{ki} is the kinetic entropy.

2.3.2 Exergy

Exergy is characterized as the maximum useful work that system can perform when it is brought into thermodynamic equilibrium with its environment. exergy destruction is defined as difference between inlet and outelet exergy. It is also defined as maximum work potential that cannot be recovered for the useful operation because of irreversibilities. Exergy balance can be expressed as follows [30].

$$Ex_{in} = Ex_{out} + I \tag{2.18}$$

Where, Ex_{in} and Ex_{out} are respectively the input and output exergy, I is the produced irreversibility during the conversion process. The exergy destruction (also called irreversibilityv I) and entropy generation are related as mentioned in the following equation:

$$I = T_0 \times \dot{S}_g \tag{2.19}$$

Where, T_0 is the ambient temperature, $\dot{S}_g$ is the entropy generation rate. Just like the entropy generation rate, irreversibility could be written as follows

$$I = I_{ch} + I_{ph} + I_{po} + I_{ki} \tag{2.20}$$

Where, I_{ch} refers to chemical irreversibility, I_{ph} refers to physical irreversibility, I_{po} is the potential irreversibility and I_{ki} is the kinetic irreversibility.

2.4 Biomass

Biomass refers to all natural matter existing within the biosphere, whether of plant or creature beginning as well as those materials gotten through their normal or artificial change. The most common biomass materials used for energy are residues, including in these both residues of forest and forest industry also residues of agriculture and waste of agro-food industry and its tributaries. Excretions of animals from the livestock farms, the organic fraction of municipal solid waste, grown energy crops including short rotation forestry are called biomass feed stocks.

2.5 Conversion of biomass wood into energy

Biomass contains energy first derived from the sun: plants absorb the Sun's energy through photosynthesis and transform carbon dioxide and water into nutrients (carbohy-0drates). The energy from these organisms can be converted into usable energy through direct and indirect ways. Biomass can be burned to create heat (direct), converted into power (direct), or processed into biofuel (indirect). Biomass can also be directly converted to energy through gasification. During the gasification process, a biomass feedstock (usually MSW) is heated to more than $700°C$ with a controlled amount of oxygen. The molecules break down and produce syngas and slag.

2.6 Gasification

Gasification is a reaction in which combustible materials are either partially oxidized or partially combusted [9]. In fact it is a thermo-chemical process involving various chemical reactions, heat and mass transfers and pressure dependencies. Gasification is one of the best transformation courses for creating a renewable energy from biomass feedstock [7]. This process is based on converting a solid fuel into a mixture of combustible gases known as 'product gas' or syngas. This technology has been in use since the 1800's for gas production from coal (town gas). In the early 1900's wood gasification was used in Europe for fuelling cars during fuel shortages [31].

2.7 Steps of Gasification

A typical gasification process involves four stages: drying, pyrolysis, partial combustion and reduction. There are relevant equations describing the chemical reactions in each of these stages.

2.7.1 Drying

Regularly, the temperature in drying zone is approximately 100–200°C. Drying is the step that moisture in biomass has to be removed before it enters pyrolysis [32]. The conversion of the quantity of humidity to water vapor takes place during drying process. This transformation takes place in the drying zone due to heat exchange between hot gases from the oxidation zone to biomass [9]. The amount of moisture discharged is equal to water vapor shaped and can be expressed in term of mass balance as shown in eq (2.14)

$$m(OH)_l = m(OH)_g \tag{2.21}$$

2.7.2 Pyrolysis

Pyrolysis is the application of warm to crude biomass, in the absence of air. During this process, biomass atoms are deteriorated into condensable gasses, tar and char at temperature between 200 and 700°C [9].

2.7.3 Oxidation

During the oxidation the temperature is approximately between (800˘1400)°C. Partial oxidation of char (C) generates carbon monoxide and heat, whereas total oxidation of char produces carbon dioxide and more heat. Sum of warm discharged during total oxidation is three times more than during partial oxidation [9].

2.7.4 Reduction

Reduction in the gasifier is realized by passing carbon dioxide CO_2 or water vapor H_2O over a bed of ruddy hot charcoal (C). Through this process, CO_2 is diminished by carbon to create two CO particles, and H_2O is diminished by carbon to create H_2

and CO. Both H_2 and CO are combustible fuel gasses, and those fuel gasses can at that point be piped off to do wanted work somewhere else.

Bouduard reaction

$$C + CO_2 \rightarrow 2CO + 172\,kJ/mol \tag{2.22}$$

Water-Gas reaction

$$C + H_2O \rightarrow CO + H_2 + 131\,kJ/mol \tag{2.23}$$

Water-Gas Shift reaction

$$CO + H_2O \rightarrow CO_2 + H_2 - 41,2\,kJ/mol \tag{2.24}$$

Mtehane reaction

$$C + 2H_2 \rightarrow CH_4 - 74,8\,kJ/mol \tag{2.25}$$

2.8 Types of gasifier

A gasifier is the reactor vessel utilized for gasification process. Gasifiers are frequently classified by the stream of the fuel source and created gas [17].

2.8.1 Fixed-bed reactors

Fixed bed gasifiers are the oldest technology utilized to produce syngas. Due to its simple development and operation, fixed bed gasifiers are broadly utilized and studied.

Depending upon the course and passage of air flow, the gasifiers are classified as up-draft, downdraft, or cross draft [17]. Gasification process depends on the type of gasifier.

- **Up-draft gasifier**
  In this process the ”gasification agent” (steam, oxygen and/or air) flows in counter-current configuration. Biomass is fed from the top of gasifier whereas gasification agent is supplied at the bottom.

- **Downdraft gasifier**

  In a downdraft gasifier, biomass and air passes in the downward direction in the lower section of the gasifier unit. This type of gasifier is known by its lower tar concentration and high char concersion [2]. Figure 2.1 shows the main difference between up-draft and downdraft gasifier which is the direction of air and fuel flow. That is why, they also named counter current and concurrent gasifier as indicated in figure 2.1 [33].

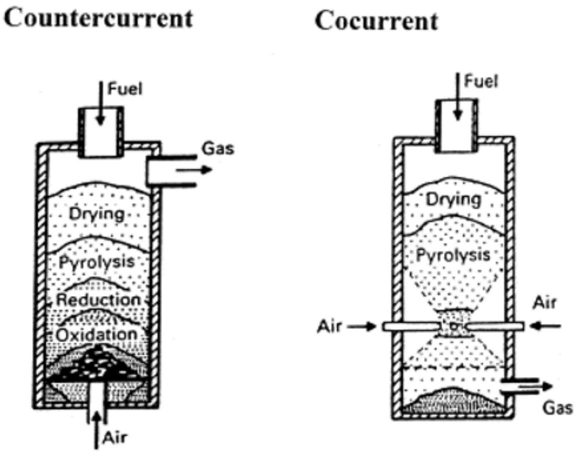

Figure 2.1: Fixed-bed gasifiers

2.8.2 Fluidized bed reactors

Fluidized bed gasification is generally utilized for coal gasification. Its advantage over settled bed gasifiers is the uniform temperature dispersion within the reduction zone. This temperature uniformity is fulfilled employing a bed of fine granular material (sand) into which air is circulated, fluidizing the bed. Two fundamental types of fluidized bed gasifiers are in current use: the circulating fluidized bed and the bubbling bed.

- **Circulating fluidized-bed**
  Circulating fluidized-bed gasifier is based on the process of persistent circulation of the bed material between the reaction vessel and a cyclone separator. The cinder is isolated in the cyclone separator and the bed material and char return back to the response vessel [34].

- **Bubbling bed gasifier**
  In the bubbling bed gasifier, biomass is supplied from the basis of the reactor through the grate. The fine bed material is set over the grate where the biomass is introduced. The temperature range is between 700 and 900°C by regulating

the air-biomass proportion. The biomass is pyrolyzed within the hot bed shaping char, vaporous compounds and tar [34].

The two concepts of fluidized bed are shown in figure 2.2 [35]:

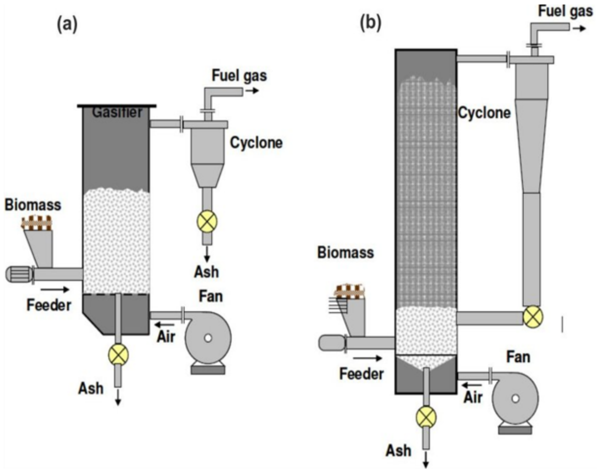

Figure 2.2: Fluidized bed gasifier

Chapter 3

Material and methods

3.1 Model design

Ecoenergetic analysis will be carried out in two systems as shown in figures 3.1 and 3.2 [21]. The figure 3.1 shows System 1 which is composed of a gasifier, a gas/water heat exchanger (gas/liquid), a wood sawdust filter and an RCX-210 engine from the Campeon MRX-50 motor pump [21]. Figure 3.2 shows System 2, which is also composed of a gasifier, a gas/air heat exchanger (gas/gas), a Wood Sawdust Filter and a Honda CG 125 Titan motorcycle engine [21].

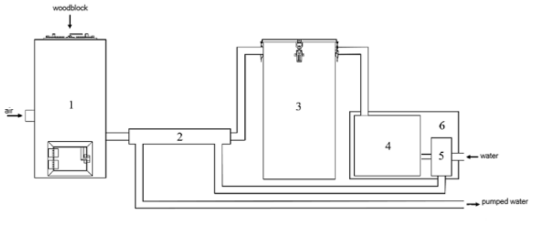

Figure 3.1: Gasifier system coupled with an RCX-210 engine

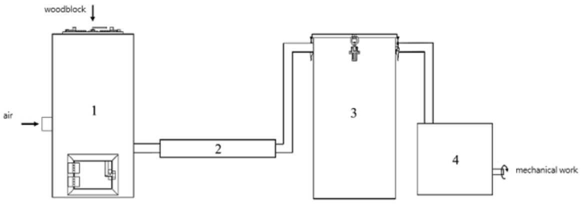

Figure 3.2: Gasifier system coupled with Honda CG 125 Titan motorcycle engine

The construction of the gasifier prototype was made in the LTM of IPB by the students: Daniel de Sousa Lemos and Licínio Fontes. The picture below represents the system with 3 components to supply the pump with syngas [21].

Figure 3.3: Prototype of the gasification system to supply the Campeon motor pump with syngas

with :
a) Gasifier.
b) Water exchanger.
c) Filter.

3.1.1 Gasifier

The gasifier is built with two major parts: the fireplace and the reservoir. Its measurement was calculated taking under consideration the stream of syngas that's straightforwardly related to the engine's fuel suction capacity. The motor CG 125 Titan (motorcycle) was taking as reference of engine with highest power. Steel, with a conduction coefficient of roughly 50 W/m^2, is the material selected to make the construction of the model.

The figure below presents a sectional drawing of the built model [21], showing the 4 main reaction zones:

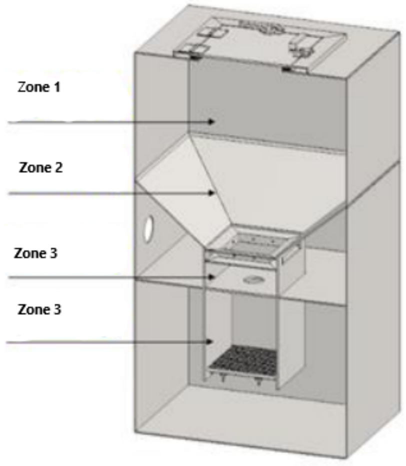

Figure 3.4: Cross-sectional drawing of the downdraft gasifier with the particular reaction zones

As mentioned in figure 3.6 [21], the downdraft gasifier includes the 4 steps of gasification process . Figure 3.6 shows the model built with Zone 1 the biomass drying region, where it receives heat from Zone 3, removing moisture from the wood. Zone 2 is where the pyrolysis reaction occurs, also using the heat of zone 3, for the decomposition of the fuel into the carbonaceous residue, condensable and non-condensable gases. In Zone 3 where the oxidation reaction takes place, which corresponds to the region from the entrance of air in the fireplace to the gasifier throat. Zone 4 is the region located just below the throat, where the reduced area generates a concentration of heat, obtaining high temperatures and allowing the thermal fractionation of the tar.

3.1.2 Heat exchanger

The heat exchanger is equipment that allows the exchange of heat from a fluid to another through natural convection. Since the gas at high temperatures can damage the engine, such a cooling system is of extreme importance in the system. In addition, gas at lower temperature is denser, allowing more fuel per unit volume. In our case, the gasification process requires two types of heat exchanger (gas/gas) and (gas/liquid). For us, the liquid is the water, the gas is the air.

3.1.3 Gas/air heat exchanger

The gas/air heat exchanger consists of a large area of contact with air (through the fins) so that, the gas is cooled by natural convection. The figure 3.4 represents its design [21].

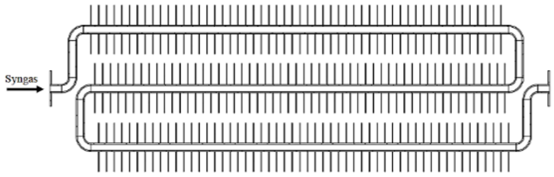

Figure 3.5: Gas/air heat exchanger

3.1.4 Gas/Water Exchanger

The gas/water heat exchanger as shown in figure 3.6 needs water from the pump as the fluid of the cooling system. It does not come into contact with the gas, but the heat exchange takes place through the walls of the tubes that contain the water. It was considered that the inlet temperature of the syngas in the exchanger is equal to the maximum outlet temperature of the syngas in the gasifier, 400°C. The syngas temperature at the heat exchanger outlet was estimated to be the ideal temperature for the engine supply that is 40°C.

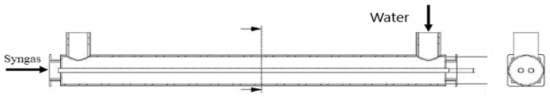

Figure 3.6: Gas/Water heat exchanger

3.1.5 Filter

The filter has the same measurements as the gasifier being a box with a segment within the center, filled with sawdust to just underneath the syngas inlet and outlet pipes. At the bottom, there are two grids destined for the homogenization of the syngas stream and ajute fabric above the grids to avoid sawdust from passing to the bottom. The figure of the filter below demonstrates the proper flow of syngas [21].

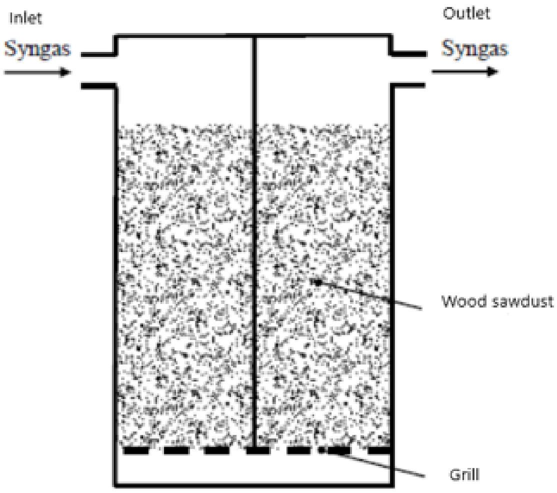

Figure 3.7: Filter

3.1.6 Motors

The installation's system requires two types of four stroke internal combustion engine: RCX-210 of the Campeon MRX-50 motor pump [21] and the engine of a Honda CG-125 Titan motorcycle [21]. Those motors will be supplied by the syngas produced after gasification as an alternative fuel. Table 3.1 shows the main properties.

Table 3.1: Properties of the Campeon MRX-50 motor pump and Honda CG-125 Titan motorcycle

Properties	Motor pump Campeon M RX-50	Motor cycle CG-125 Titan
Model's motor	RCX-210	
Maximum power (kW)	4.78	9.19
Cylinder (cc)	212	124.10
Rotation (rpm)	1800	9000

Figure 3.8: Motor pump Campeon MRX-50

Figure 3.9: Motor cycle CG-125 Titan

3.2 Applied model

This study aims to evaluate the design already presented above from a thermo ecological point of view. This kind of assessment requires the applications of some parameters such as equivalence ratio ER, surface velocity SV, ecological coefficient of performance ECOP, pollutant indicator π_p, ecological efficiency ϵ and effective ecological power density EFFECPOD. The gasification model is presented in two differents designs (the same gasifier). The first system is coupled to Motor pump Campeon MRX-50 and the second one is with Motor cycle CG-125 Titan.

3.2.1 SV calculation

SV measurement as already mentioned in section 2.2.4 needs the determination of the throat section of the gasifier. In a previous study made by Lemos [36], the gasifier dimensionement was carried out. The reservoir and the fire place were calculated. The narrowest section in the gasifier correspond to the throat part, in which the diameter is presented as follows

$$D_t = \sqrt{\frac{4 \times \dot{V}_{syngas}}{\pi \times B_t}} \tag{3.1}$$

Where B_t is the maximum amount that the gasifier produces gases, and it was set equal to 0.9 m^3/cm^2h.

Table 3.2: Design of the throat section of gasifier for two types of engines

Parameter	unit	Motor pump Campeon MRX-50	Motor cycle CG-125 Titan
D_t	mm	30	45
S	mm^2	544	1596

By [36], the gasifier was dimensioned based on the highest value of the diameter that corresponds to the gasifier coupled with motor cycle CG-125 Titan which equal to 45 mm. In this case, the choice of diameter will also be applicable with the gasifier coupled with Motor pump Campeon MRX-50. Which explains that eq 2.4 will be calculated with S equal to 1596 mm^2.

3.2.2 ECOP calculation

As shown in section 2.2.6, ECOP calculation requires the determination of entropy generation rate. With the considering of negligible amount of kinetic and potential entropy, this parameter is divided into two major parts physical and chemical as expressed in eq 3.2.

$$\dot{S}_g = \dot{S}_{ph} + \dot{S}_{ch} \tag{3.2}$$

Just like entropy S, I is divided into physical and chemical one as written in eq 3.3.

$$I = I_{ph} + I_{ch} \tag{3.3}$$

By considering that filter irreversibility is negligible, total irreversibility of the system is presented in eq 3.4.

$$I_{tot} = I_g + I_{He} + I_M \tag{3.4}$$

Taking into account eq 3.3, eq 3.4 will be written as follows:

$$I_{tot} = I_{ph}^{G} + I_{ch}^{G} + I_{ph}^{He} + I_{ch}^{He} + I_{ph}^{M} + I_{ch}^{M} \tag{3.5}$$

Based on eq.3.5, physical and chemical irreversibilities of the system could be written as follows

$$I_{ph} = I_{ph}^{G} + I_{ph}^{He} + I_{ph}^{M} \tag{3.6}$$

$$I_{ch} = I_{ch}^{G} + I_{ch}^{He} + I_{ch}^{M} \tag{3.7}$$

It should be noticed that chemical irreversibility of the heat exchanger is negligible. Considering the chemical reaction that took place within the gasifier and the motors, chemical irreversibility is determined following eqs 3.8...3.13 and based on material balance of each one of gasifier and motor.

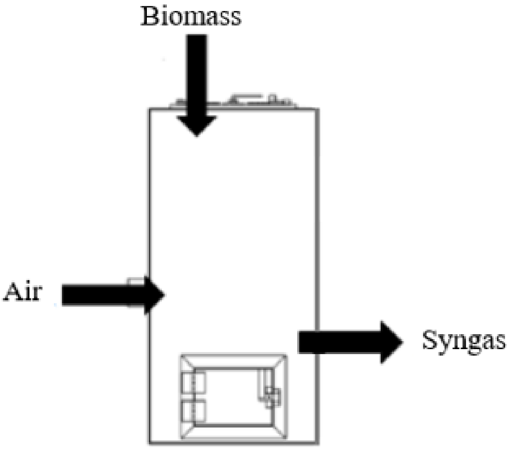

Figure 3.10: Material balance of gasifier

As shown in figure 3.10, reactants of gasifier are air and biomass, syngas is the main product. Gasifier chemical irreversibility is written as follows

$$I_{ch}^{G} = Ex_{biomass} + Ex_{air} - Ex_{syngas} \tag{3.8}$$

The gasification process is coupled to two types of internal combustion engines. That is why, combustion reaction that took place within the motors have to be considered. As shown in figure 3.11, reactants of motor are syngas and air, water and (CO_2) are the main products.

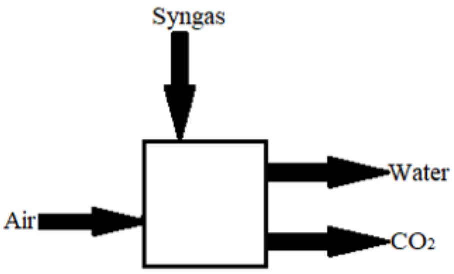

Figure 3.11: Material balance of the motor

Chemical irreversibility of the motor is presented in eq. 3.9.

$$I_{ch}^{M} = Ex_{syngas} + Ex_{air} - Ex_{water} - Ex_{CO_2} \tag{3.9}$$

It sould be mentioned that gasifier and motor are supplied with air to ensure the combustion. This air is taken under the same conditions (dead state), which makes it possible to consider equally the exergy of air supplying the gasifier and the exergy of air supplying the engine.

Substituing eq.3.8 and eq.3.9 in eq.3.7, total chemical irreversibility will be expressed as follows

$$I_{ch} = Ex_{biomass} + 2 \times Ex_{air} - Ex_{water} - Ex_{CO_2} \tag{3.10}$$

This study use the wood pellets as biomass, its exergy is determined following eq.3.13 [37].

$$Ex_{biomass} = n_{biomass} \times \beta \times LHV_{biomass} \tag{3.11}$$

Where the coefficient β in terms of atomic ratios is given by eq.3.12 [37].

$$\beta = \frac{1.0414 + 0.0177\frac{H}{C} - 0.3328\frac{O}{C}\{1 - 0.0537\frac{H}{C}\}}{1 - 0.4021\frac{O}{C}} \tag{3.12}$$

The mol biomass ratio is given in eq.3.13.

$$n = \frac{m}{M} \tag{3.13}$$

Where m is the mass of biomass and M is its molar mass. $LHV_{biomass}$ is the low heat value of biomass. Calculation of biomass energy needs determination of its composition and its LHV. According to previous study, wood composition is estimated as shown in table 3.3 [38].

Table 3.3: Biomass composition presented by components in percentage of dry basis weight wt% d.b.

Ultimate analysis	Value
C	49.45
H	4.60
O	38.08
N	0.34
Cl_2	0.03
ASH	1.37

Air, water and CO_2 have physical and chemical exergy. Physical exergy is expressed as follows:

$$Ex_{ph} = (h - h_0) - T_0(s - s_0) \tag{3.14}$$

Where h and s are enthalpy and entropy of gas species at operating temperature and pressure; while h_0 and s_0 are the corresponding values at standard operating state (dead state), which are taken as $298\,K$ and 1 atm [37].

Introducing eq.3.3 and eq.3.5 in eq.2.9, ECOP will be expressed as follows:

$$ECOP = \frac{\dot{W}}{(Ex_{biomass} + 2 \times Ex_{air} - Ex_{water} - Ex_{CO_2}) + I_{ph}^{G} + I_{ph}^{He} + +I_{ph}^{M}} \tag{3.15}$$

For more consistency, irreversibility results should be in kW. Exergy of air, water and CO_2 are found in kJ/mol, that is why, these results will be multiplied by the molar rate of each substances. CO_2 and H_2O are the products of the syngas combustion reaction. Number of mole of them is determined based on chemical progress table.

3.2.3 Pollutant indicator calculation

Pollutant indicator measurement requires the determination of CO_2 emission which in turn requires the determination of syngas composition.

According to table 3.1, syngas obtained is composed of varying amounts of H_2, N_2, CO_2 and CO. Syngas does not contains any of sulphuric dioxide, nitrogen oxide and particulate matter. In that case, carbon dioxide emission CO_{2e} will be limited to the amount of carbon dioxide CO_2 in the produced gas. Therefore, we will obtain this equation

$$CO_{2e} = CO_2 \tag{3.16}$$

Based on eq.3.16, pollutant indicator is presented as follows

$$\pi_p = \frac{CO_2}{LHV_{syngas}} \tag{3.17}$$

3.2.4 EFECPOD calculation

As mentioned in section 2.2.9, EFECPOD is expressed as follows

$$EFECPOD = \frac{\eta_{ef} P_{ef}}{\frac{T_1}{T_0}.a.V} \tag{3.18}$$

This parameter will be calculated following the next indications:

- $\eta_{ef} = \frac{P_{ef}}{\dot{Q}_{syngas}}$, effective efficiency of system and taken 33% from [21].
- P_{ef} is the effective power as proposed in the original literature and it is equivalent to the output power of the motor ($\dot{w}$) in this study already mentioned in table 3.1
- V is the motor's volume which mentioned in table 3.1
- T_0 is the ambient temperature $25°C$ (is also T_{min}).
- T_1 is the inlet temperature of gas in the motor $40°C$ after being cooled by the heat exchanger [21].
- T_{max} is the maximum temperature $600°C$.

Chapter 4

Results and discussion

4.1 ER Results

The LHV of the syngas produced varies between [5,5.9] MJ/kg [21]. Mass of air and mass of wood flow rate ranges between two values for each system as shown in table 4.1. Air-wood mass stochiometric ratio is the air–fuel ratio for complete combustion. According to [39], this parameter is proposed equal to 6.364. By using eq.2.2, and based on the values of mass flow rate of air and fuel (wood), equivalence ratio is determined as shown in table 4.1.

Table 4.1: Equivalence ratio of both gasification systems

Parameter	Units	System 1	System 2
LHV_{syn}	(MJ/Kg)	[5.0,5.9]	[5.0,5.9]
$\dot{m}_{air}$	(Kg/s) $10^{(-3)}$	[0.79,0.94]	[2.32,2.74]
$\dot{m}_{wood}$	(Kg/s)$10^{(-3)}$	[0.50,0.59]	[1.49,1.73]
Air-wood ratio		[1.58,1.59]	[1.57,1.58]
Air-wood stochiometric ratio		6.364	6.364
Equivalence ratio		0.25	0.25

ER is found equal to 0.25, table 4.1. Air-wood ratio is approximately set equal for both systems with 4 different mass rate input of both air and wood. The air-wood stochiometric ratio is set equal to 6.364 which explains the obtaining of a single value of ER for the gasifier working in both systems. ER ranges between 0.2 and 0.4 in biomass gasification [7]. The obtained result did not exceed the limits of the range proposed in the literature.

4.2 SV Results

The throat section is already designed, as well as the gasifier, under the largest diameter which is equal to 45 mm. By applying eq. 2.4, SV is calculated. Table 4.2 presents the SV measurement for both systems.

Table 4.2: Results of superficial velocity

Parameter	Units	Motor pump Campeon MRX-50	Motor cycle CG-125 Titan
Volume flow rate	$(m^3/s)\ 10^{-3}$	1.36	3.99
Throat section S	$m^2\ 10^{-3}$	1.596	1.596
Surface velocity SV	m/s	0.852	2.5

The SV for the system working with motor pump Campeon MRX-50 and for the system working with motor cycle CG-125 Titan is respectively equal to 0.852 and 2.5 m/s, table 4.2. According to Yamazaki et al SV of the downdraft gasification with air varies between 0.3-0.7 m/s [40]. The lowest tar yield (0.7%) was obtained at 0.4 m/s SV, and the highest was obtained at 0.7 m/s. In this study, SV obtained is out of the range proposed in the literature. Which explain that high content of tar is in the produced gas and which approximatively can be more than 0.7%. According to this outcomes, it seems that the studied syngas is not suitable for operation of an IC engine. It will be recommended to add a tar removal equipement in the gasification design.

4.3 Pollutant indicator results

LHV of the gas produced range between [5.0,5.9] (MJ/m^3). This parameter in (MJ/kg) is obtained by dividing these values by the syngas mass unit which is equal to 0,59 (kg/ m^3) [21]. Table 4.3 shows the measurement of syngas pollutant indicator relying on eq.2.11.

Table 4.3: syngas pollutant indicator calculus

Parameter	Units	Value
LHV_{Syngas}	MJ/kg	[8.470,10.000]
Carbon dioxide equivalent CO_{2e}	kg/kgf	0.151
Pollutant indicator π_p	kg/MJ	[0.015,0.018]

In table 4.3, carbon dioxide emission CO_{2e} is almost equal to 0.151 kg/kgf. Syngas pollutant indicator obtained varies between 0.015 and 0.018 kg/MJ. By [28], hydrogen and sulphur are presented as virtual fuels used as comparative elements. Hydrogen is the substance that corresponds to the minimum value of pollutant indicator which is equal to 0 kg/MJ, while for sulphur it is mentioned equal to 134 kg/MJ, and it corresponds to the higher value comparing to other substances. As [27], natural gas with carbon dioxide emission CO_{2e} equal to 5.51 kg/kgf has 0.154 kg/MJ as pollutant indicator. Pollutant indicator obtained in this study, is approximately 10% lower than the one obtained by [27], which explains that syngas is more efficient than natural gas from environmental perspective. Table 4.6 illustrates the difference of pollutant indicator of some fuels showing that syngas of this study presents the higher ecological impact.

Table 4.4: Comparison of pollutant indicator of some fuels powering an internal combustion engine

Fuel	Carboen dioxide emission	LHV	Pollutant indicator	Ref
Unity	kg/kgf	MJ/kg	kg/MJ	
Natural gas	2.73	47.1	0.06	[41]
Diesel	8.53	44.40	0,19	[41]
Gasoline	5.89	47.30	0.12	[41]
Syngas*	0.43	-	0.08	[3]
Syngas	0.15	8.47	0.02	-

Figure 4.1 confirm that syngas with lower pollutant indicator occupies the first position as the best fuel from an ecological point of view.

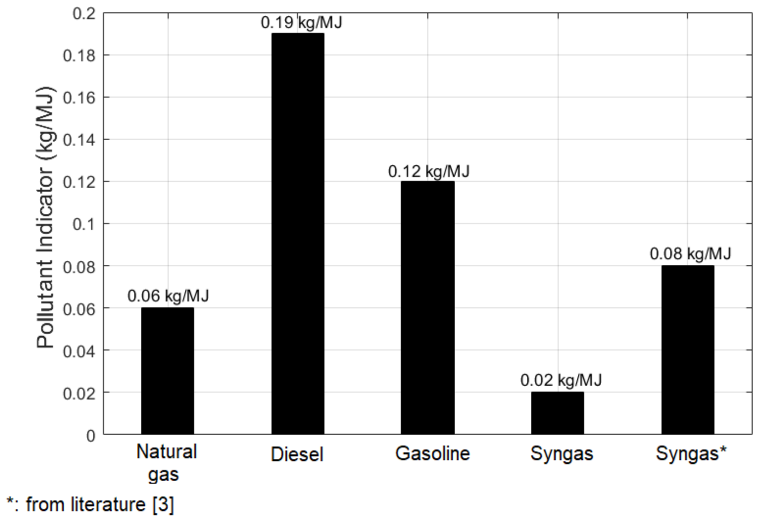

Figure 4.1: Natural gas, diesel, and gasoline and syngas pollutant indicator

4.4 Ecological efficiency results

The energy efficiency of global system is already calculated in [21]. It was found to be equal to 22% for both systems. Having the pollutant indicator and the energetic efficiency allows the calculation of the ecological efficiency measuring. Based on eq.2.12, this parameter is determined as shown in table 4.5

Table 4.5: Ecological efficiency of the system

Parameter	Symbol	Units	Value
Energetic efficiency	η	%	22
Pollutant indicator	π_p	(kg/MJ)	[0.015,0.018]
Ecological efficiency	ϵ	kg/MJ	[96.2,96.7]

The ecological efficiency of the produced gas is varying between [96.2,96.7] %. According [27], lignite is found with ecological efficiency ranging between 0.3 and 0.4 knowing that it corresponds to 2.045 kg/MJ as pollutant indicator. Syngas ecological efficiency is also found equal to 80.80445 % for 0.15035 as system efficiency [1]. In that study, is given by varying the particulate matter MP in the produced gas.

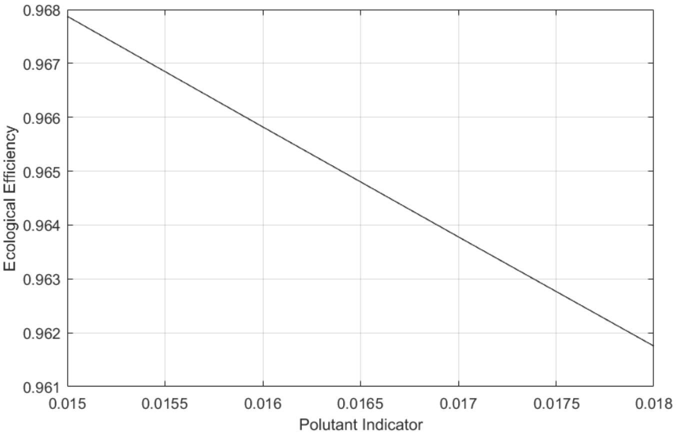

Figure 4.2: Ecological efficiency results based on pollutant indicator variation

Ecological efficiency depends to a great extent to pollutant indicator. As it is indicated in figure 4.2, the curve of ecological efficiency is decreasing in function of pollutant indicator which explain that they are inversely proportional. Higher values of pollutant indicator diminue the ecological efficiency as well as the quality of syngas from an ecological point of view.

A comparison between the ecological efficiency achieved by burning the syngas in internal combustion engine and ecological efficiencies obtained from burning some fuels such as natural gas, diesel and gasoline is in table 4.6 that shows differenec between the fuels [41].

Table 4.6: Comparison of ecological efficiency of some fuels powering an internal combustion engine

Fuel	Ecological efficiency	Ref
Unit	%	
Natural gas	91.95	[41]
Diesel	77.35	[41]
Gasoline	82.22	[41]
Syngas*	80.8	[3]
Syngas	96.45	-

In table 4.6 syngas is categorized as the best fuel from an ecological point of view, regarding its higher value of ecological efficiency. Then, it comes natural gas and gasoline. Diesel is classified in the last position.

4.5 ECOP results

ECOP is an ecological objective function that gives the data for the rate of the entropy generation or the rate of availability loss. Its measurement requires calculations to total irreversibility of the system and power output of both motors. Motor's power output is determined as indicated in table 4.7.

Table 4.7: Power output of the motors

Engines	Power range (kW)
Motor pump Campeon M RX-50	[2.16 ,2.57]
Motor cycle CG-125 Titan	[6.3,7.49]

According to table 4.7, power output of motor pump Campeon M RX-50 and motor cycle CG-125 Titan vary respectively between [2.16 ,2.57] kW and [6.3,7.49] kW [21]. As already mentioned in section 3.2.2, total irreversibility is divided by chemical and physical one. Following irreversibility results from [21] and based on eq.3.6, total physical irreversibility of both systems is calculated as shown in table 4.8.

Table 4.8: Physical irreversibility measurement

	component	Irreversibilities (kW)
System 1	Gasifier	[1.63,1.93]
	Heat exchanger	[0.35, 0.38]
	Motor	[1.30,1.54]
I_{ph} (kW)		[3.28,3.85]
System 2	Gasifier	[4.77,5.62]
	Heat exchanger	[0,99,1.00]
	Motor	[3.82,4.55]
I_{ph} (kW)		[9.58,11.17]

As presented in table 4.8, physical irreversibilities of both systems are respectively obtained between [3.28,3.85] kW and [9.58,11.17] kW.

While chemical reactions that occur in both of gasifier and motors, chemical irreversibility has to be taken into account. This parameter requires calculations of air, biomass CO_2 and syngas exergies.

The air supply for the gasifier and motor is frech air (dead state), thus assumed in standard conditions. Based on eq.that highlights the physical exergy and assuming that the operating conditions of air almost equal to the standard conditions, physical exergy of air will be neglected.

Generally, the products of hydrocarbon combustion are CO_2 and water. Due to the exhaust pipe cooling, thermal conditions of the combustion products are decreased. In fact, from the combustion chamber of the engine to its exhaut pipes, temperature is decreasing from $1427°C$ to around $[149, 260]°C$. Assuming the difference between the operating and standard conditions of both water and (CO_2) and based on eq.3.14, physical exergy of these substances is calculated as shown in table 4.9.

Table 4.9: Water and carbon dioxide physical exergies

Substance	Formula	Exergy (KJ/mol)
Water	H_2O	[-3.18,-5.59]
Carbon Dioxide	CO_2	[-3.6,-6.63]

Table 4.10 shows chemical exergy of these substances [42].

Table 4.10: Air water and (CO_2) chemical exergies

Substance	Formula	Exergy (KJ/mol)
Air	-	1.3
Water	H_2O	1.3
Carbon dioxide	CO_2	20

Determining number of mole of products ((H_2O) and (CO_2)) need calculation of number of mole of reactant using eq.3.13.

Table 4.11: Syngas mass rate

Gas	Mass fraction	$\dot{m}(kg/s)$
CO_2	0.156	0.000125
CO	0.173	0.000138
H_2	0.018	0.000014
N_2	0.654	0.000523

As [21], mass flow rate of the syngas equal to 0.8×10^{-3} kg/s. Mass flow rate of air required to carry out the combustion reaction in the engine is determined based on the air-syngas stochiometric ratio mentioned in 2.2.5. Mass flow rate of (O_2) is calculated following the rule of air is composed of 21% (O_2) and 79% (N_2).

Table 4.12: Reactants properties

	Formula	$\dot{m}(kg/s)$	$\dot{n}(mol/s)$
Reactants	CO	0.000138	0.000008
	H_2	0.000014	0.000007
	Air	0.000960	0.000033
	O_2	0.000202	0.000006

Chemical progressing table allows us to determine limited reactant which is (O_2) as well as the number of mole of products.

Table 4.13: Products properties

	Formula	$\dot{n}(mol/s)$
Products	CO_2	0.000013
	H_2O	0.000013

Chemical and physical exergies of air, (H_2O) and (CO_2) are demonstrated in table 4.14.

Table 4.14: Chemical and physical exergies of air, (H_2O) and (CO_2)

	$EX_{ph}(kW)$	$EX_{ch}(kW)$
Air	-	0.0000429
H_2O	[-0.00004134, -0.00007267]	0.000169
CO_2	[-0.0000468, -0.00008619]	0.00026

Biomass LHV is determined equal to 18 MJ/kg as [38]. The proposed chemical formula for wood is $CH_{1.769}\ O_{0.617}\ N_{0.026}\ S_{0.001}$ [43]. By applying eqs.3.11; 3.13, biomass exergy is determined as shown in table 4.15.

Table 4.15: Calculation of wood exergy for system 1 and 2

Parameter	Units	System 1	system 2
$m_{biomass}$	10^{-3}kg	[0.50,0.59]	[1.470,1.730]
$\eta_{biomass}$	mol/s	[0.015,0.018]	[0.044,0.052]
$Ex_{biomass}$	kW	[226.8,272.16]	[665.28,786.24]

With $M_{biomass}$ of 33.27 g/mol, of 0.84 and $LHV_{biomass}$ of 18 MJ/kg, results obtained shows that for both systems exergy from biomass is respectively varying between [226.8,272.16] kW and [665.28,786.24] kW. Based on eq.3.15 and relying on results from table 4.7 and 4.8, chemical irreversibility is determined. By applying eq.3.15, ECOP is found for both systems as shown in table 4.16.

Table 4.16: ECOP measurement

	System 1	System 2
W (kW)	[2.16,2.57]	[6.3, 7.49]
I_{ph} (kW)	[3.28,3.85]	[9.58, 11,17]
I_{Ch}(kW)	[226.79, 272,16]	[665.19, 786.23]
ECOP	[0.00931,0.00938]	[0.0093,0.00934]

According to table 4.16, ECOP ranges between [0.00931,0.00938] for system 1 and between [0.0093,0.00934] for system 2. These results are almost 36 % lower than ECOP in the literature [13] where, it is found 0.026 as minimum value and 0.051 as maximum value.

Matlab is used to plot ECOP for three cases. The first case is by varying I_{Ch} under its interval with keeping W and I_{ph} constant. The second case is by varying I_{ph} under its interval with keeping W and I_{Ch} constant.The third case is by varying W under its interval with keeping I_{Ch} and I_{ph} constant. Figures below illustrated results obtained from this simulation.

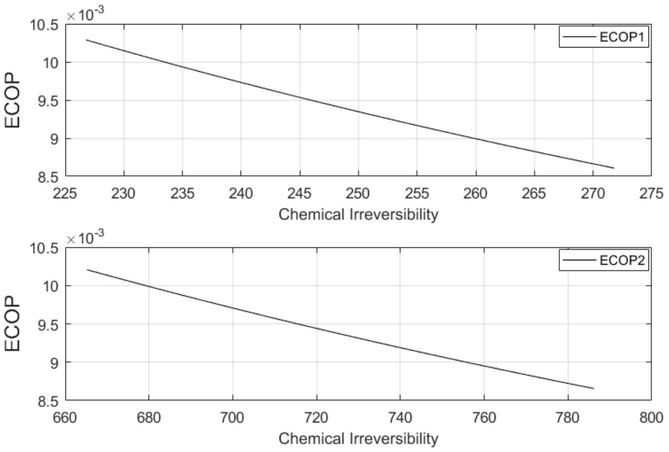

Figure 4.3: ECOP results based on chemical irreversibility variation for system 1 and system 2

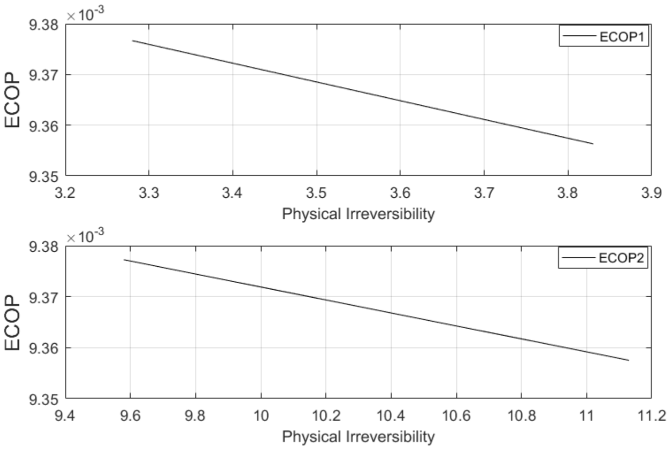

Figure 4.4: ECOP results based on physical irreversibility variation for system 1 and system 2

As it can be seen in figures 4.3 and 4.4, ECOP is decreasing while irreversibilities are increasing, proving that they are inversely proportional. These results shows the negative effect of irreversibilities on system's performance. So, it should be noticed that optimizing system performance can be based on minimizing the losses (irreversibility rate) within a system.

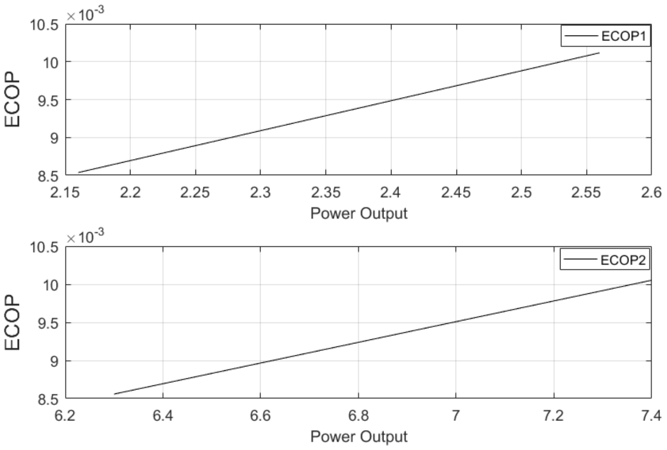

Figure 4.5: ECOP results based on power output variation for system 1 and system 2

According to figure 4.5, ECOP is increasing in function of motors power output, allowing to say ECOP in positively influenced by increasing the power output

4.6 EFECPOD results

As mentioned in section 2.2.8, EFECPOD is a performance characteristic of thermal systems. Using eq.2.13, EFECPOD is determined in table 4.17.

Table 4.17: EFECPOD results

Parameter	Units	Motor pump Campeon M RX-50	Motor cycle CG-125 Titan
$\dot{Q}_{syngas}$	kW	[6.48,7.71]	[18.92,22.51]
$\dot{W}$	kW	[2.16,2.57]	[6.30,7.49]
V	$10^{-4}m^3$	2.12	1.241
$EFECPOD$	kW/m^3	[87.55,104.17]	[436.26,518.67]

Table 4.17 illustrates results obtained of EFECPOD with 0.33 as η_{eff}, 1.6 as T_1/T_0 and 24.00 for α. EFECPOD is respectively varying between [87.55,104.17] and [436.26,518.67] kW/m^3 for system 1 and system 2. According to [44], EFECPOD in influenced by the cycle design and the operating conditions such like equivalence ratio, turbine speed, mass rate and inlet temperature (T_1).

In this study, effect of variation inlet temperature (T_1) of the engine on EFECPOD will be examined through figure 4.6.

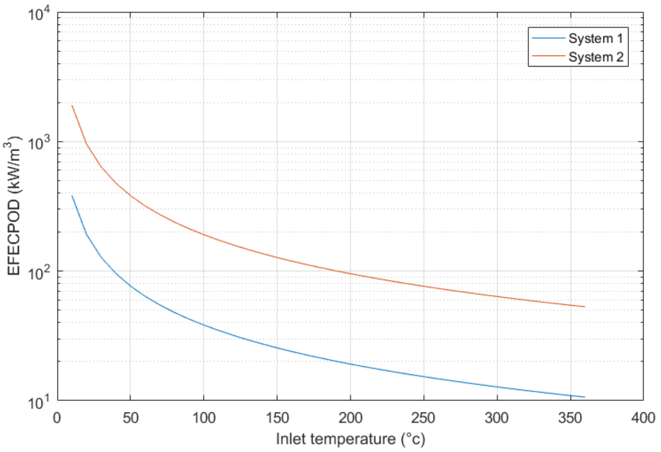

Figure 4.6: The variation of EFECPOD with different inlet temperature for both systems

According to figure 4.6, EFECPOD reaches its maximum, when the temperature tends towards 0. On the other hand, when the temperature tends towards its limits, EFECPOD turns towards 0. Thus, these results pointed out that EFECPOD decrease with increasing inlet temperature at constant effective efficiency η_{eff},and temperature cycle ratio α. Which mean that reducing inlet temperature have positive impact on EFECPOD.

Chapter 5

Conclusions and Future Work

5.1 Conclusions

This study illustrates an evaluation of a gasification system coupled to a combustion engine considering ecological aspects. Theses analysis were carried out to evaluate the syngas quality and the ecological performance of the system.

$ECOP$ is calculated taking into account the chemical and physical irreversibilities of the system. Results obtained varies between [0.00931,0.00938] for system 1, and [0.0093,0.0094] for system 2 showing that a high level of irreversibilities decreases $ECOP$, thus, decreases the system performance. $EFECPOD$ is found [87.55,104.17] kW/m^3 for system 1, and [436.26,518.67] kW/m^3 for system 2 . The effect of inlet temperature on this parameter was examined showing that reducing temperature affects positively $EFECPOD$.

Ecological efficiency of the syngas varies between [96.2,96.7] %. A comparison between the ecological efficiency achieved by burning the syngas in the internal combustion engine and ecological efficiencies obtained from burning fossil fuels in internal combustion engine allowing to say that burning syngas has the best environmental sustainability. Also, pollutant indicator of syngas was determined between [0.015,0.018] kg/MJ and compared to other fuels pollutant indicators showing the lowest value, thus, the highest performance. SV is 0.852 m/s for system 1 and 2.5 m/s for system 2, which was found out of the range proposed in the literature . ER is equal to 0.25 for both systems presenting tar formation in the syngas produced. According to these findings, the syngas quality parameters highlight that this syngas presents a good alternative fuel regarding its higher values of ecological efficiency comparing to other fuels with the exception of SV. This result can be explained by the lack of tar removal technologies in the system either cyclone inside the gasifier or tar removal after the gasifier.

5.2 Future work

- Analysing the quality of syngas produced by biomass gasification other than wood presenting bigger low heat value.
- Improve system filtration by adding cyclone (inside the gasifier) or tar removal.
- Conduct an economic analysis to study the feasibility of implementing the system

Bibliography

[1] R. A. M. Boloy, J. L. Silveira, C. E. Tuna, C. R. Coronado, and J. S. Antunes, "Ecological impacts from syngas burning in internal combustion engine: Technical and economic aspects," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 9, pp. 5194–5201, 2011a.

[2] J. D. Martínez, K. Mahkamov, R. V. Andrade, and E. E. S. Lora, "Syngas production in downdraft biomass gasifiers and its application using internal combustion engines," *Renewable Energy*, vol. 38, no. 1, pp. 1–9, 2012a.

[3] R. A. M. Boloy, J. L. Silveira, C. E. Tuna, C. R. Coronado, and J. S. Antunes, "Ecological impacts from syngas burning in internal combustion engine: Technical and economic aspects," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 9, pp. 5194–5201, 2011b.

[4] M. Puig-Arnavat, J. C. Bruno, and A. Coronas, "Review and analysis of biomass gasification models," *Renewable and sustainable energy reviews*, vol. 14, no. 9, pp. 2841–2851, 2010.

[5] J. A. Ruiz, M. Juárez, M. Morales, P. Muñoz, and M. Mendívil, "Biomass gasification for electricity generation: Review of current technology barriers," *Renewable and Sustainable Energy Reviews*, vol. 18, pp. 174–183, 2013.

[6] E. Açıkkalp, "Performance analysis of irreversible solid oxide fuel cell–brayton heat engine with ecological based thermo-environmental criterion," *Energy Conversion and Management*, vol. 148, pp. 279–286, 2017.

[7] W. Paengjuntuek, J. Boonmak, and J. Mungkalasiri, "Energy efficiency analysis in an integrated biomass gasification fuel cell system," *Energy Procedia*, vol. 79, pp. 430–435, 2015.

[8] E. E. S. Lora and K. R. Salomon, "Estimate of ecological efficiency for thermal power plants in brazil," *Energy Conversion and Management*, vol. 46, no. 7-8, pp. 1293–1303, 2005.

[9] A. Susastriawan, H. Saptoadi, *et al.*, "Small-scale downdraft gasifiers for biomass gasification: A review," *Renewable and Sustainable Energy Reviews*, vol. 76, pp. 989–1003, 2017.

[10] T. Yamazaki, H. Kozu, S. Yamagata, N. Murao, S. Ohta, S. Shiya, and T. Ohba, "Effect of superficial velocity on tar from downdraft gasification of biomass," *Energy & Fuels*, vol. 19, no. 3, pp. 1186–1191, 2005.

[11] Y. Ust, B. Sahin, and O. S. Sogut, "Performance analysis and optimization of an irreversible dual-cycle based on an ecological coefficient of performance criterion," *Applied energy*, vol. 82, no. 1, pp. 23–39, 2005.

[12] Y. Ust and B. Sahin, "Performance optimization of irreversible refrigerators based on a new thermo-ecological criterion," *International Journal of Refrigeration*, vol. 30, no. 3, pp. 527–534, 2007.

[13] H. Caglayan and H. Caliskan, "Thermo-ecological analysis of industrial kilns," *Journal of environmental management*, vol. 241, pp. 149–155, 2019.

[14] J. D. Martínez, K. Mahkamov, R. V. Andrade, and E. E. S. Lora, "Syngas production in downdraft biomass gasifiers and its application using internal combustion engines," *Renewable Energy*, vol. 38, no. 1, pp. 1–9, 2012b.

[15] C. Franco, F. Pinto, I. Gulyurtlu, and I. Cabrita, "The study of reactions influencing the biomass steam gasification process," *Fuel*, vol. 82, no. 7, pp. 835–842, 2003.

[16] V. Kirsanovs, A. Zandeckis, D. Blumberga, and I. Veidenbergs, "The influence of process temperature, equivalence ratio and fuel moisture content on gasification process: A review," *Research Gate*, 2014.

[17] E. R. Widjaya, G. Chen, L. Bowtell, and C. Hills, "Gasification of non-woody biomass: A literature review," *Renewable and Sustainable Energy Reviews*, vol. 89, pp. 184–193, 2018.

[18] I. Narvaez, A. Orio, M. P. Aznar, and J. Corella, “Biomass gasification with air in an atmospheric bubbling fluidized bed. effect of six operational variables on the quality of the produced raw gas,” *Industrial & Engineering Chemistry Research*, vol. 35, no. 7, pp. 2110–2120, 1996.

[19] S. Wongchanapai, H. Iwai, M. Saito, and H. Yoshida, “Performance evaluation of an integrated small-scale sofc-biomass gasification power generation system,” *Journal of Power Sources*, vol. 216, pp. 314–322, 2012.

[20] A. Inayat, M. M. Ahmad, S. Yusup, and M. I. A. Mutalib, “Biomass steam gasification with in-situ co2 capture for enriched hydrogen gas production: a reaction kinetics modelling approach,” *Energies*, vol. 3, no. 8, pp. 1472–1484, 2010.

[21] C. F. Chaves, “AnÁlise termoenergÉtica de um gaseificador.” Master thesis in Portugal, 2020.

[22] R. P. Bates1 and K. Dölle, “Syngas use in internal combustion engines,” 2017.

[23] Y. Üst, B. Sahin, and A. Kodal, “Ecological coefficient of performance (ecop) optimization for generalized irreversible carnot heat engines,” *Journal of the Energy Institute*, vol. 78, no. 3, pp. 145–151, 2005.

[24] M. H. Ahmadi, M. A. Ahmadi, M. Mehrpooya, and M. Sameti, “Thermo-ecological analysis and optimization performance of an irreversible three-heat-source absorption heat pump,” *Energy Conversion and Management*, vol. 90, pp. 175–183, 2015.

[25] Y. Ust, O. Sogut, B. Sahin, and A. Durmayaz, “Ecological coefficient of performance (ecop) optimization for an irreversible brayton heat engine with variable-temperature thermal reservoirs,” *Journal of the Energy Institute*, vol. 79, no. 1, pp. 47–52, 2006.

[26] G. Gonca and B. Sahin, “Thermo-ecological performance analysis of a joule-brayton cycle (jbc) turbine with considerations of heat transfer losses and temperature-dependent specific heats,” *Energy Conversion and Management*, vol. 138, pp. 97–105, 2017.

[27] M. Cârdu and M. Baica, “Regarding a new variant methodology to estimate globally the ecologic impact of thermopower plants,” *Energy conversion and management*, vol. 40, no. 14, pp. 1569–1575, 1999.

[28] I. A. de Castro Villela and J. L. Silveira, “Ecological efficiency in thermoelectric power plants,” *Applied thermal engineering*, vol. 27, no. 5-6, pp. 840–847, 2007.

[29] G. Gonca, “Exergetic and thermo-ecological performance analysis of a gas-mercury combined turbine system (gmcts),” *Energy Conversion and Management*, vol. 151, pp. 32–42, 2017.

[30] M. E. Echegaray, M. Castro, G. D. Mazza, and R. Rodriguez, “Exergy analysis of syngas production via biomass thermal gasification,” 2016.

[31] S. Kumar and S. Shukla, “A review on wood downdraft gasifier plant design for biomethane gas production,” in *2015 International Conference on Energy Systems and Applications*, pp. 57–62, IEEE, 2016.

[32] M. Gürtürk and H. F. Oztop, “Energy and exergy analysis of a rotary kiln used for plaster production,” *Applied thermal engineering*, vol. 67, no. 1-2, pp. 554–565, 2014.

[33] R. Warnecke, “Gasification of biomass: comparison of fixed bed and fluidized bed gasifer,” 2000.

[34] T. K. Patra and P. N. Sheth, “Biomass gasification models for downdraft gasifier: A state-of-the-art review,” *Renewable and Sustainable Energy Reviews*, vol. 50, pp. 583–593, 2015.

[35] A. Horvat, “A study of the uncertainty associated with tar measurement and an investigation of tar evolution and composition during the air-blown fluidised bed gasification of torrefied and non-torrefied grassy biomass,” 2016.

[36] D. D. E. S. Lemos, *Gaseificador Downdraft Para Operação De Motores De Combustão Interna De Pequena Potência.* PhD thesis, 2019.

[37] C. Sreejith, C. Muraleedharan, and P. Arun, “Energy and exergy analysis of steam gasification of biomass materials: a comparative study,” *International Journal of Ambient Energy*, vol. 34, no. 1, pp. 35–52, 2013.

[38] G. Gündüz, N. Saraçoğlu, and D. Aydemir, “Characterization and elemental analysis of wood pellets obtained from low-valued types of wood,” *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, vol. 38, no. 15, pp. 2211–2216, 2016.

[39] M. Prins, K. Ptasinski, and F. Janssen, “Thermodynamics of gas-char reactions: first and second law analysis,” *Chemical Engineering Science*, vol. 58, no. 3-6, pp. 1003–1011, 2003.

[40] S. Y. N. M. S. O. S. S. Takashi Yamazaki, † Hirokazu Kozu and T. Ohba, “Effect of superficial velocity on tar from downdraft gasification of biomass,” 2005.

[41] C. R. Coronado, J. A. de Carvalho Jr, J. T. Yoshioka, and J. L. Silveira, “Determination of ecological efficiency in internal combustion engines: The use of biodiesel,” *Applied Thermal Engineering*, vol. 29, no. 10, pp. 1887–1892, 2009.

[42] J. Szargut, D. R. Morris, and F. R. Steward, “Exergy analysis of thermal, chemical, and metallurgical processes,” 1987.

[43] Y. Lenis and J. Pérez, “Gasification of sawdust and wood chips in a fixed bed under autothermal and stable conditions,” *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, vol. 36, no. 23, pp. 2555–2565, 2014.

[44] G. Gonca, “Application of a novel thermo-ecological performance criterion: effective ecological power density (efecpod) to a joule-brayton cycle (jbc) turbine,” *Journal of Thermal Engineering*, vol. 3, no. 5, pp. 1478–1488, 2017.