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Numerical Analysis of a Combined Heat and Power Generation Technology from Residual Biomasses

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Abstract: Energy valorization of organic waste material is nowadays an assessed practice of circular economy. Combined heat and power (CHP) technologies based on biomass gasification represent viable substitutes to traditional energy conversion units based on combustion, whose need has recently experienced a huge growth, due to the increasing concerns about the release of greenhouse gases (GHGs) emissions and the related effects on climate changes. At present, only a few solutions have yet achieved a level of full development for commercialization. One of them is the system developed by CMD, the CMD ECO20, made of a gasifier, a syngas cleaning system and a spark ignition internal combustion engine working as a co-generator. In the present work, a numerical model is developed to study this system into detail and search for optimal controlling parameters. The simulation relies on a combined use of the Thermoflex™ environment and a proper one-dimensional (1D) model of the engine module built within GT-Suite®. An original contribution is given to the turbulent combustion model that accounts for the laminar flame speed of the specific syngas. The numerical model, that covers the entire biomass-to-energy conversion process, is validated under real operative conditions. The final purpose of the work is the optimization of input parameters, as the initial biomass moisture content, the equivalence ratio at the gasifier or the timing of spark advance, to maximize the system electrical energy output.

Key words: Biomass, CHP, gasification, internal combustion engine, syngas, wood chip.

1. Introduction

Reducing greenhouse gas (GHG) emissions and safeguarding the planet from climate changes and global warming are major concerns of daily life. A dedicated agreement was signed during the so-called "Conference of the Parties" (COP21) held in Paris in 2015 and came into force on November 4th 2016, after a ratification by 195 countries. The Paris Agreement substantially promotes a radical transformation of the energy sector that can only be achieved by an enhanced use of renewable energy sources (RES) [1]. Renewables are therefore expected to become the center of the energy mix in Europe in the near future, from technology development to mass production and deployment, from small-scale to larger-scale, integrating local and more remote sources, within both subsidized and competitive business models.

Decarbonisation will indeed require a large quantity of biomass for heat, electricity and transport. Among the various uses of biomass as source for heat and power, one of the most interesting is certainly gasification, with the obtained synags combustion in a reciprocating internal combustion engine (ICE), especially at the small or micro scale of power. Biomass thermochemical conversion is known since a long time, but a renewed interest is today registered just towards gasification as a valid alternative to incineration, especially for its lower environmental impact. The process is conditioned by numerous variables, such as the biomass composition and its moisture content and the air-to-biomass ratio. The composition of the product gas is therefore not constant,

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not even its calorific value and the presence of undesired elements such as tars and particulate matter.

Gasifiers are complex systems requiring time to be mounted and to be put into operation, whose performance can be hardly quantified uniquely.

Nowadays, the used reactors [2] to gasify a pre-treated biomass differ from each other for:

- gasifying agent;
- type of contact between feedstock material and gasifying agent;
- type and rate of heat transfer;
- residence time of the fed material into the reaction zone.

Different technological solutions can be implemented in order to obtain efficient plant configurations. In particular, the type of contact of the biomass with the gasification agent may be in countercurrent, co-current, or cross flow, and the heat can be transferred from the outside or directly in the reactor using a combustion agent; the residence time can be of the order of hours or minutes.

Various validated models have been developed to predict the performance of a gasifier. These are fundamental to help identify the sensitivity of performance to variation of operating and design parameters [3]. Models can be helpful for design, prediction of operational behavior, prediction of emissions during normal conditions, start-up, shut-down, change of fuel, change of load and to lessen problems related to char and tar formation.

Just to make some examples, Jarungthammachote et al. [4], developed a thermodynamic equilibrium model based on the evaluation of the equilibrium constants to predict the composition of the producer gas in a downdraft gasifier. In this model the reaction temperature is calculated if the amount of oxygen is known, and vice versa. Altafini et al. [5] simulated a sawdust gasifier using an equilibrium model based on the minimization of the Gibbs free energy.

As the use of the syngas is considered in ICEs, on the other hand, Banapurmath et al. [6] studied the performance of a 4-cylinder spark ignition (SI) engine, highlighting that the power reduction is mainly attributed to the lower heating value (LHV) of the used fuel. Lapuerta et al. [7] studied the limit of power in an SI engine due to the volume of gas/air mixture entering the engine cylinders that reduces the volumetric efficiency. Another important parameter to be considered is indeed the energy density of the producer gas/air mixture that mainly depends upon the concentration of the combustible components in the gas. For a syngas the stoichiometric ratio of air/combustible is between 1.0 and 1.3, compared to 17 for methane. Less than 50% in volume composition of a syngas is made of combustible components (H_2 21.3%, CO 19.4% and CH_4 1% for a syngas product from treated wood) [8], so the energy density of the producer gas/air mixture is lower than for other traditional fuels. The theoretical value of power de-rating when a natural gas engine is switched to operate on producer gas is of about the 30% [9].

The present work focuses on the development of a whole system model of a micro-cogeneration unit powered by woodchips and based on gasification and syngas use in an SI ICE.

The considered micro combined heat and power (mCHP) unit is composed by a gasifier, a cleaning and cooling system, a 4 Cylinder ICE and exchangers for heat recovery from the exhaust gases, and an electric generator. The final purpose of the study is to estimate the effects of some important parameters on the electric output, as the biomass initial moisture content and the equivalence ratio at the gasifier, by evaluating the change obtained in the composition of the raw syngas not only from a thermodynamic point of view (such as the variation of LHV), but also in its oxidation properties within the ICE. The behavior of the entire micro-cogeneration plant is indeed to be considered as a whole, due to the strong inter-dependency upon processes as a preliminary biomass drying is made by the engine exhaust gases and as the enthalpy of these last obviously depends on the gasification performance and ICE operation. The model is validated by exploiting data on a properly made experimental campaign and proves to be adequate to the scopes of the CMD ECO20 optimization.

2. Description of the Gasification Process

Gasification is a thermochemical process consisting in the conversion of solid or heavy liquid fuels into gaseous ones by incomplete oxidation at high temperature (800-1,000 °C) with controlled sub-stoichiometric amount of oxygen (pure or contained in air or steam): the equivalence ratio, i.e. the ratio of oxidant supplied to that required for complete combustion, is typically 0.25-0.40.

The gasification reactions have as result gaseous products (carbon dioxide, water, carbon monoxide, hydrogen, and gaseous hydrocarbons), small quantities of char (solid product), ash and condensable compounds (tars and oils). Steam, air or oxygen, are supplied as oxidizing agents. The gas produced can be standardized in its quality and it is easier and more versatile to be used than the original biomass. In fact, it can be used to power gas reciprocating ICE and in gas turbines [10], or as a chemical feedstock to produce liquid fuels.

The main steps involved in the gasification process can be categorized as upstream processing, gasification and downstream processing.

Upstream processes include:

- size reduction;
- use of gasifying agents;
- drying;
- pyrolysis.

Upstream processes include processing of the biomass to make it suitable for gasification operations. Size reduction is needed to obtain appropriate particle sizes; the choice of the gasification agent is important for gasification efficiency; drying is needed to achieve appropriate moisture content and reach a value of LHV of interest. Pyrolysis, on the other hand, can be shown as the first step of real conversion. The most important gasification reactions are:

Partial combustion:

$$C + {}^{1}\!/_{2}\, O \rightarrow CO + 110.6 \frac{kJ}{mol} \tag{1}$$

Total combustion:

$$C + O_2 \rightarrow CO_2 + 393.7 \frac{kJ}{mol} \tag{2}$$

Boudouard reaction:

$$C + CO_2 \rightarrow 2CO + 172.5 \frac{kJ}{mol} \tag{3}$$

Water-gas heterogeneous reaction:

$$C + H_2O \rightarrow CO + H_2 + 131.4 \frac{kJ}{mol} \tag{4}$$

Natural gas formation reaction:

$$C + 2H_2 \rightarrow CH_4 - 75 \frac{kJ}{mol} \tag{5}$$

Water-gas homogeneous reaction:

$$CO + H_2O \rightarrow CO_2 + H_2 - 41.2 \frac{kJ}{mol} \tag{6}$$

Natural gas reforming reaction:

$$CO + 3H_2 \rightarrow CH_4 + H_2O + 206.4 \frac{kJ}{mol} \tag{7}$$

The partial combustion reaction of carbon produces only the 28% of the max heat obtainable with total combustion, leaving the remaining 72% as heating value available in the producer gas. Depending on the amount of oxygen introduced, the total combustion reactions may advance or not, in order to raise temperature of gasification, to allow the endothermic reactions of Boudourad and gasification. The other reactions determine the relationship between the other components of the syngas [11, 12].

Downstream treatments are cooling and cleaning of the raw syngas. Cooling allows a first heat recovery, estimable at 21.6% of the energetic input of the system, lowering the gas temperature up to 40 °C, fundamental for a correct cleaning. That allows the removal of fly-ashes, particulate and sulfuric acids, resulting in improved emissions.

3. The mCHP Unit CMD ECO20

The CMD ECO20 is a micro-scale CHP system powered with biomass, under development by the Italian Company Costruzioni Motori Diesel S.p.A. (CMD), whose headquarter is in San Nicola La Strada (Caserta, Italy).

It is an integrated system combining a downdraft gasifier, syngas cleaning devices, an SI ICE and an electric generator. Waste heat recovery is realised through proper heat exchangers along the engine cooling circuit and the exhaust gases line. CMD ECO20 generates electrical and thermal energy through thermo-chemical decomposition of organic materials (biomass) at high temperature with minimal amounts of oxygen, and combustion of the released syngas in the reciprocating engine. Gasification produces an extremely clean syngas. Pureness is further increased through a process of cleaning, cooling and filtering, before secondary conversion in a 3.0 L GM Vortec I-4 engine. The crankshaft of this last is connected to an alternator MeccAlte, mod. ECP 028, able to produce electric power up to 20 kW_{el}. Thermal power up to 40 kW_{th} is also delivered. The CMD ECO20 is designed to process wooden biomass of G30 size (1.50 to 3.00 cm).

The type of biomass that can be used for CMD ECO20 can be chosen from a variety of products: scraps of forestation, wine shoots, branches pruning, nut shells, coconut shells, hazelnut shells, chestnut shells, almond shells, olive pits, apricot pits, peach pits, stalks of tobacco, corn stalks, cane residues whose moisture content is between 15% and 30% in mass. Greater values of humidity imply loss of performance of the device due to the negative effect on the syngas calorific value.

The system is a fully automated machine, electronically managed at every stage of operation: from the automatic loading of the biomass into the hopper, the start-up and operation of the gasification reactor, the starting of the generator up to the realization of the parallel connection with the electric national grid. The control system manages the ash discharge, the condensed matter, the biochar and can act with suitable strategies (until the system shutdown) in the case of possible failures, thanks to the presence of proper sensors and automatic safety alarms. The CMD ECO20 has a web service interface through which it is possible to analyse the stored data, monitor the device parameters, manage the system via a simple internet connection, without an operator present in the operative environment.

The most important technical characteristics of CMD ECO20 are shown in Table 1 [13]:

Table 1 Technical characteristics of CMD ECO20.

CMD ECO20	
Available maximum power (nominal value)	20 kW_{el} @50 Hz
Biomass consumption	1.2 kg/kWh_{el}
Run time of hopper filling	15 m^3/hr = 11 hrs
Start up time	15-45 min.
Biomass consumption	1.2 kg/kWh
CHP (nominal values) (engine cooling/exhaust heat recovery)	30 kW_{th}/10 kW_{th}
Emissions (Italian regulation 152/06 part V-All. I part III)	NO_x = 158 <350 (mg/Nm^3) SO_2 = 31 < 35 (mg/Nm^3) PM = 2.5 < 5 (mg/Nm^3)

4. Description of the Whole System Model

A numerical model of the considered CMD ECO20 system is developed within the Thermoflex™ software (Thermoflow Inc.), one of the various thermal engineering commercial tools for the design of power and cogeneration units. Compared with other tools, Thermoflex™ is a more general fully-flexible software for modeling a great variety of thermal systems, i.e. not only gas turbines or steam cycles. It is a modular program with a graphical interface that allows the user to assemble a plant model from icons representing over one hundred different components (customized elements can also be created).

An option menu is associated with each component: the user can define all design parameters (efficiencies, head or heat losses, desired pressure and temperature, etc.). Information concerning the simulated plant must be provided as:

- overall plant data (power output, electrical efficiency, heat rate, etc.);
- characteristic features of the various components (size and temperature-heat transfer diagram of a heat exchanger, steam expansion line in the enthalpy-entropy diagram for a turbine, produced or absorbed power, etc.);
- values of the thermodynamic parameters (temperature, pressure, enthalpy, steam quality in addition to mass flow rate), which may override the user's input data if necessary, in every point of the plant.

It must be specified that results implicitly refer to full-load steady conditions, while the transient phase is not analyzed. Another major Thermoflex™ feature consists in the broadness of its library, both concerning working mediums (gases, fuels, refrigerants, etc.) and, above all, pre-built commercial power plants, i.e. gas turbines and internal combustion engines. In particular, models of ICEs are very important for the purposes of this work, because they cannot be assembled starting from simpler components, but can only be used as single default machines [14].

The CMD ECO20 System is modeled as specified in the following.

4.1 Gasifier

This component is represented with a user-defined gasifier, which requests in input both the fuel and the oxidant flows. A fuel preparation unit is present that is a constraint deriving from considering large coal plants, where fuel is fed after being mixed with a water or nitrogen stream because these plants are normally pressurised. This component is not found on the micro-scale because gasifiers operate at ambient pressure and the fuel can be fed mechanically. In the here considered plant configuration, this water/nitrogen source is not present: for this reason, its mass flow rate has always been fixed equal to zero in all simulations.

As already mentioned, the software requests in input a series of data for materials entering the reactor.

For the biomass it is necessary to provide:

- temperature;
- pressure;
- mass flow-rate;
- proximate and ultimate analysis on wet basis.

In terms of composition, the biomass actually used in the system is woodchips, with G30 dimension.

For the air flow, the software requests:

- temperature;
- pressure;
- mass flow rate.

For the gasification process, it is necessary to set the:

- gasifier type: oxygen-blown gasifier or air-blown;
- pressure of gasification process;
- air/fuel ratio or gasifier temperature;
- slag exit temperature;
- carbon conversion.

Fig. 1 represents the here used gasifier model. Actually, a heat exchanger is added to the gasifier to model the exhaust gas flow at the top of the gasifier that is used on the real plant to reduce the moisture content of the biomass. In fact, in input, the fuel presents 25% of moisture content but the interaction with hot gases gives the possibility to dry a part of the water. The detail of this preliminary process is given in Fig. 2.

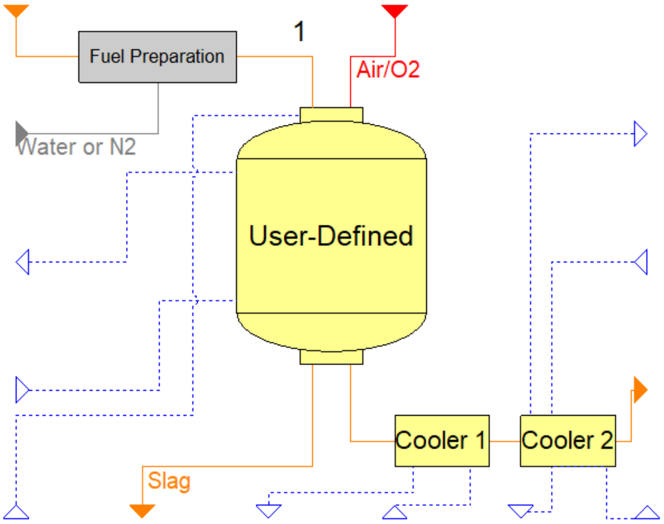


Fig. 1 Thermoflex icon for gasifier.

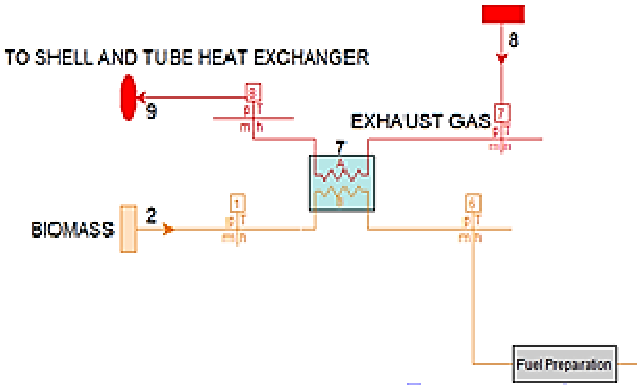


Fig. 2 Interaction of the CMD ECO20 ICE exhaust gases with the raw biomass.

4.2 Cooling and Cleaning System

Thermoflex™ provides models for all the components that characterize the cooling and cleaning section: theoretically, a cleaning section downstream of the gasifier could be assembled. Nevertheless, the syngas exiting the gasifier is already clean, being composed only by CO, CO_2, CH_4, H_2, N_2 and Ar, free ash. So, it is possible to concentrate the cleaning section into two simple components: a heat exchanger that has the role of cooler, simulating the temperature decrease and head losses along the process, and a moisture separator that takes away water eventually formed downstream. However, the temperature reduction that characterizes the syngas in its passage through the cyclone is not characterized. So, in the complete scheme, a component will be added that simply simulates the heat transfer and temperature decrease in this component. The used scheme is represented in Fig. 3.

4.3 Internal Combustion Engine

The ICE component with its cooling circuit is described in Thermoflex as shown in Fig. 4. The radiator is represented by a heat exchanger and an air compressor in order to simulate the fan action. The exhaust gases, after the reduction of its moisture content at the top of the gasifier, continue their path into a shell and tube heat exchanger that completes the waste heat recovery process.

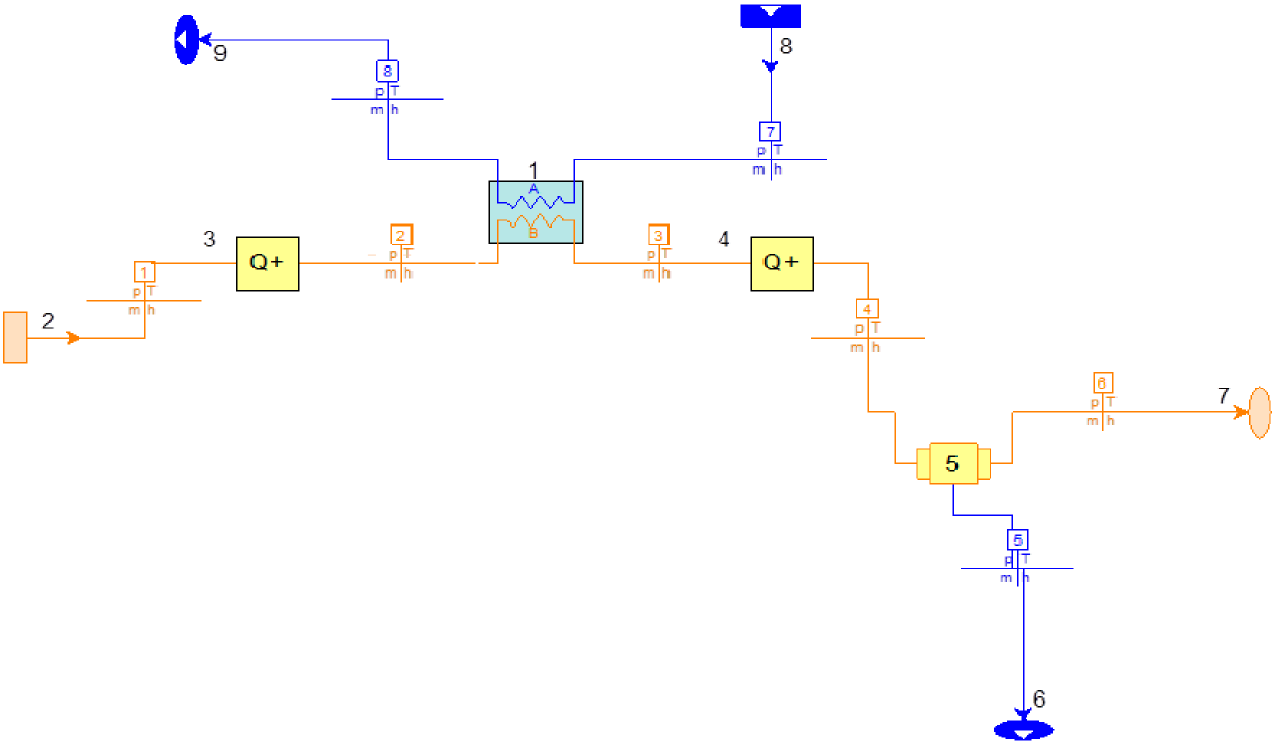


Fig. 3 Thermoflex schematization of the CMD ECO20 cooling and cleaning system.

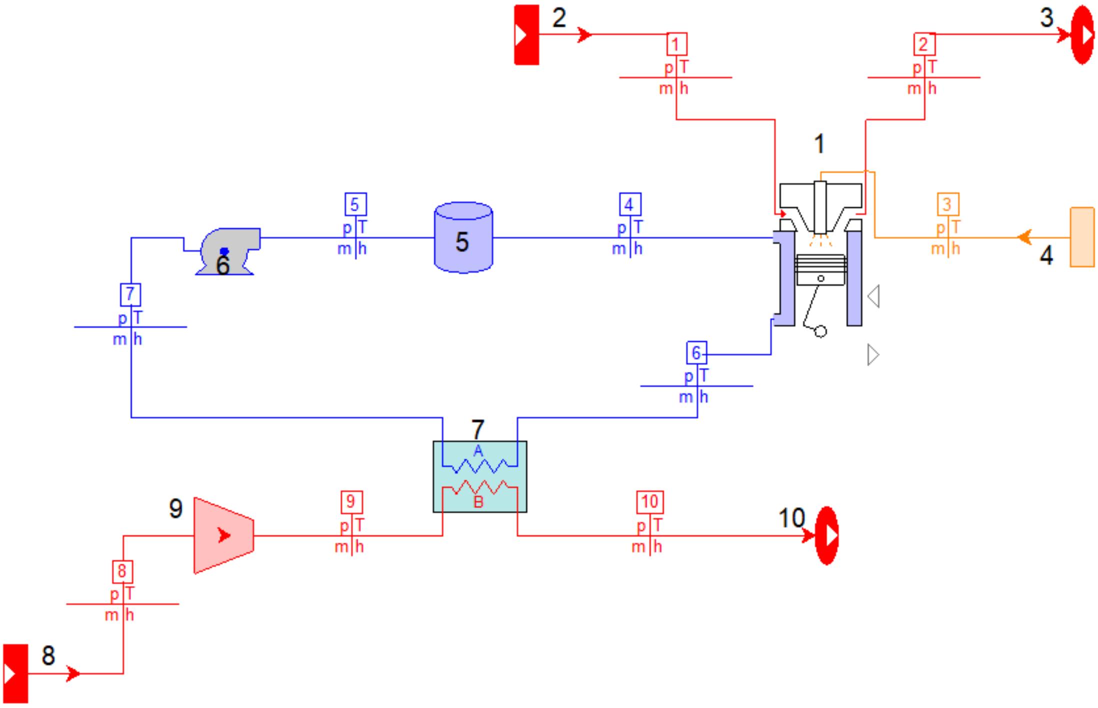


Fig. 4 Schematization of ICE and cooling system.

As for the gasifier, also the ICE requests a series of input data. For the syngas and air mixture the following input data are needed:

- mass flow rate;
- temperature;
- pressure.

A user-defined engine is used that allows a greater flexibility in modeling. On the other hand, the ICE work can be calculated by providing other fundamental information:

- primary energy in input (as product of syngas mass flow rate and its LHV);
- desired power;
- primary heat recovery (heat exchanged with cooling water);
- mass flow rate of exhaust gases and their temperature.

In this way the software can close also the energy balance.

4.4 Heat Exchanger

Thermoflex^{TM} provides three types of general heat exchangers, which transfer heat between two streams, of any fluid type and in any phase in a counter-flow arrangement. The three types differ only for the input variables that are defined by the user and they are:

General HX-E: the user-defined variable is the effectiveness of the heat exchanger that is used by the software to calculate the heat transfer between the two streams, their exit states and the size, defined by the product between the heat exchange area and the heat exchange coefficient "UA". This component is useful for modelling heat exchangers in design situations where the fluid states entering the heat exchanger are not known, making it difficult to guess what the desired exit states should be.

General HX-S: the user-defined variable is the outlet state of either of the streams that is used to calculate the heat transfer, the exit state of the other stream and to size the heat exchanger by finding its "UA". This component is used when the user knows a desired exit state at the design-point.

General HX-SS: the amount of heat transferred to (or from) the main stream is either specified directly or calculated fixing its outlet state. The outlet state of the secondary stream is also specified and thus its required flow rate is calculated by this component [14].

4.5 Final Model

The whole mCHP system model is created by assembling all the previously described sub-models for components. The final schematization is represented in the following Fig. 5. It is possible to note orange lines that represent the biomass/syngas stream, blue ones represent the water in the cooling circuit of the ICE and in the heat recovery circuit while the red colour is used for the air/exhaust circuits.

4.6 Model Limits

During the implementation of the CMD ECO20 system model in Thermoflex^{TM}, a very important limit of the software was noted. Indeed, the user-defined reciprocating engine requests in input some unknown parameters, such as the temperature of the exhaust gas and the produced mechanical power that are generally specified on technical leaflets of commercial engines, but that indeed depend upon the specific fuel composition and engine operating mode. In the here considered system, fuel is a syngas whose quality in terms of composition and LHV depends upon gasification; in other words several variables such as biomass composition, gasifier operating features (equivalence ratio (ER) and carbon conversion), air temperature and others affect the biomass conversion rate and the so-called cold gas efficiency of the gasifier, hence they affect syngas quality. Moreover, another limit of the user-defined engine component is the impossibility to consider a nominal power lower than 30 kW. For these reasons it was essential to resort to another approach to model the internal combustion engine fed with the syngas produced in the gasifier.

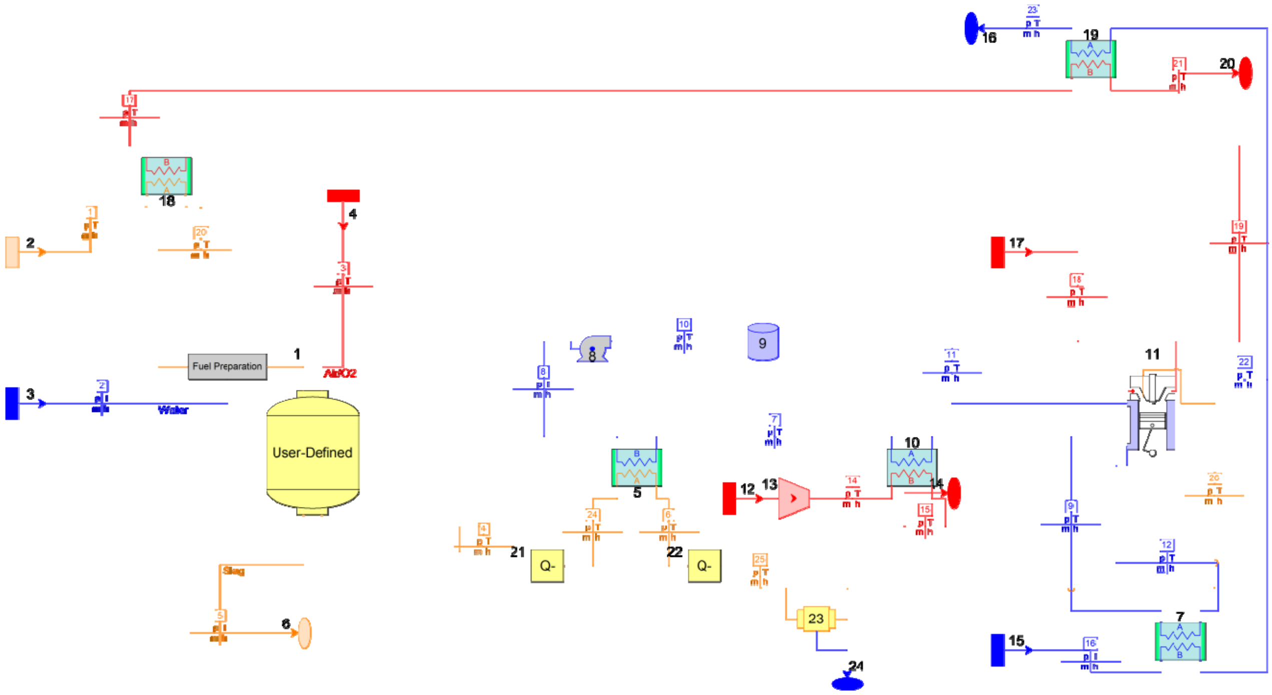


Fig. 5 The CMD ECO20 system model.

5. Description of the 0-1D Engine Model

In order to avoid the just described stiffness of the engine block in Thermoflex^{TM}, the ICE was modeled following a 0-1D code in the GT-Suite$^{®}$ environment, thus obtaining a good prediction of the engine operation with a reduced computational cost. This software contains the GT-Power module that allows simulating fluid-dynamic, thermal, mechanical, electromagnetic, chemical systems and the related controllers. It is mainly used for the simulation of vehicles, alternative internal combustion engines, transmission systems and generic propellers.

The first step to get the engine model is its geometry definition. Data not available from the technical catalog were detected using the "reverse engineering" technique. In particular, the less accessible parts of the head, like the intake and exhaust ducts, were modeled using a silicone rubber mold. The intake and exhaust valve timing and the dimensions of the combustion chamber were detected by precision measuring instruments, such as a comparator and a centesimal caliber and goniometer.

After the construction of the ICE scheme of Fig. 6, boundary conditions are set as following:

- the engine is powered from two reservoirs, one is representative of air, the other of syngas. Pressure and temperature of both fluids are calculated with the previously said Thermoflex^{TM} gasifier and cooling system model;
- the syngas composition is the same obtained through the gasifier model;
- the engine aspires a mixture of air and syngas in stoichiometric proportions. The air mass flow rate is managed through a PID controller that regulates the opening of a the engine throttle valve;
- the discharge has a slight overpressure, due to the presence of other components downstream of the engine. The pressure drop in these components is the one calculated with Thermoflex^{TM}.

The next step in the engine model assessment is related to the need of defining an appropriate combustion model. The classic Wiebe equation makes possible to calculate the amount of mass burned according to the crank angle, imposing the trend of the burnt mass

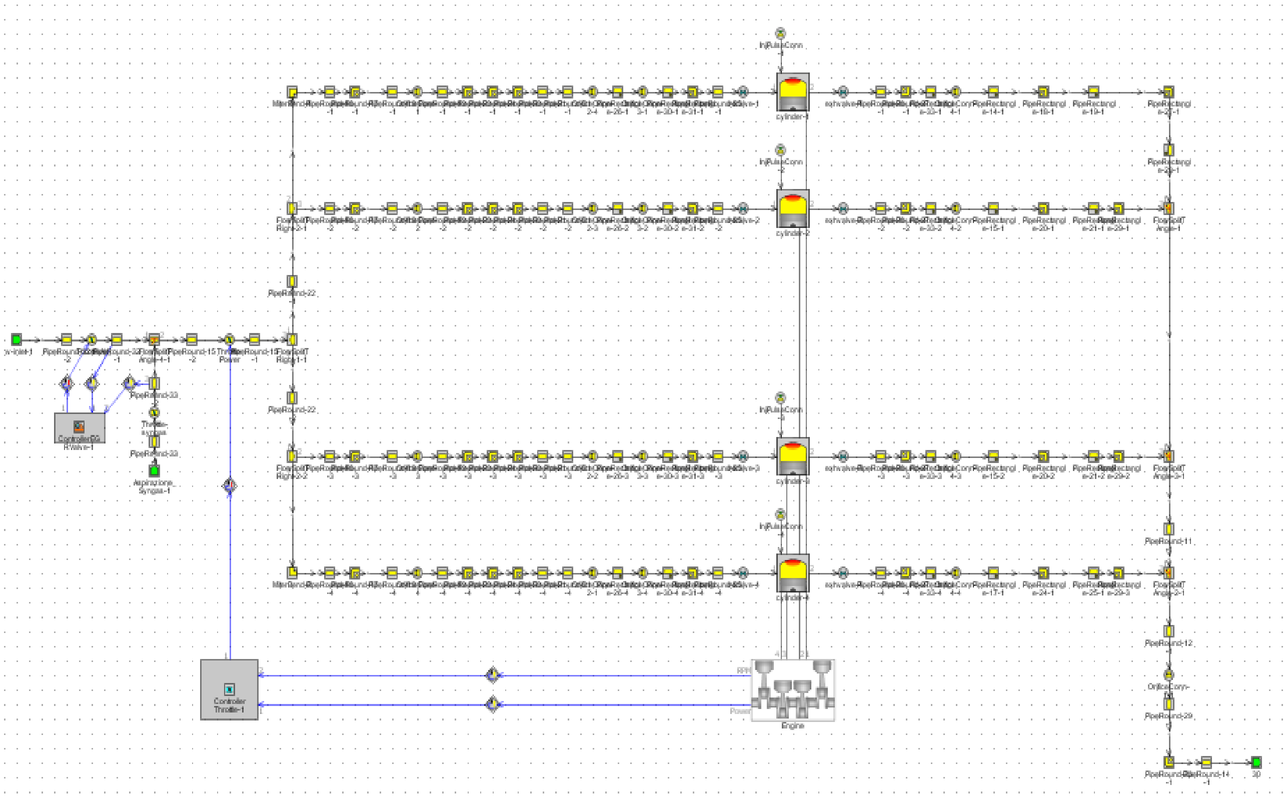


Fig. 6 Engine model in GT-Suite®.

fraction with a sigmoid function, with a very low predictive index. To overcome this problem, a predictive model of turbulent combustion (called EngCylCombSITurb) is used, which allows quantifying the flame speed, emissions and knocking in spark ignition engines. Obviously this approach is more complex than the one based on the Wiebe function, so it required a deeper analysis. After the definition of an equivalent combustion chamber, the most difficult step was the definition of Laminar Flame Speed model. GT-Power provides models for the most common fuels, but no one of them is syngas. As the model is customizable, it was properly designed for the specific fuel here considered as described in the following.

The laminar flame speed (S_L) is calculated by using the following equation [15]:

$$S_L = S_{ref}\left(\frac{T_u}{T_{ref}}\right)^{\alpha}\left(\frac{p}{p_{ref}}\right)^{\beta}$$

where:

S_{ref} represents the laminar flame speed in a reference state ($T_{\text{ref}} = 300$ K; $p_{\text{ref}} = 1$ bar);

T_{u} is the temperature of the unburned mixture;

α is the exponent of the relationship between T_{u} and T_{ref} and is a function of the equivalence ratio. It provides indications on the increase of the laminar flame speed as a function temperature;

β is the exponent of the relationship between the pressure and the reference one and is a function of the equivalence ratio. It provides indications on the decrease of laminar flame speed with pressure.

The scientific literature provides tools to derive these quantities [7, 16]. The Chemkin® software is here used to study the behavior of the laminar flame speed as a function of the equivalence ratio of the mixture in the ICE for the syngas under examination. The Chemkin® code allows calculating the chemical kinetics of reactions using different mechanisms and, consequently, the laminar flame speed of oxidizer/combustible mixtures under different conditions.

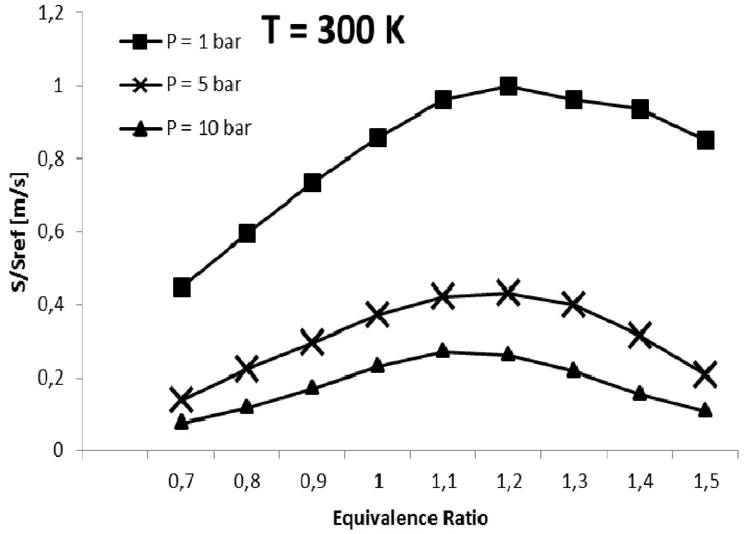


Fig. 7 Laminar flame speed for syngas/air mixtures at different pressure levels.

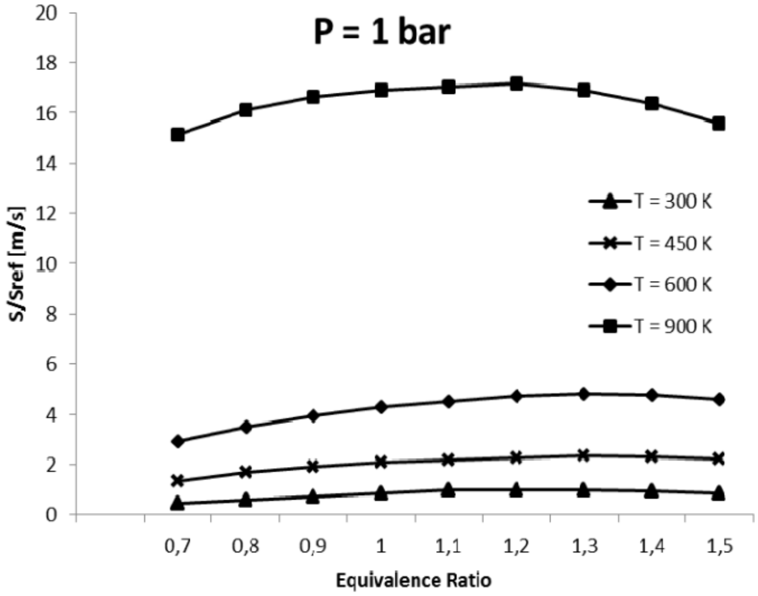


Fig. 8 Laminar flame speed for syngas/air mixtures at different temperatures.

Among the available mechanisms, the Grimech 3.0 kinetic scheme was chosen, designed to model methane combustion, including NO formation and re-burn chemistry. Figs. 7 and 8 show the laminar flame speed results as, respectively, the trend with respect to pressure and temperature for a mixture made of air and the syngas obtained by woodchip gasification in the CMD ECO20 system under real operation. Different conditions are indeed considered to calculate an average value of the exponents α and β that represent, respectively, the increase and decrease of the laminar flame speed with temperature and pressure.

The determination of the laminar flame speed allows evaluating all parameters requested by GT-Power to build the combustion model and get the value of the turbulent flame speed in the engine combustion chamber.

6. Model Validation

The validation of the developed numerical model of the CMD ECO20 system is made with respect to experimental data obtained from a proper campaign. A "baseline" condition of the whole system is assumed to get measurements of the following variables:

- temperature at different points of the gasifier;
- temperatures along the syngas line;
- pressures along the syngas line;
- composition of the processed biomass;
- composition of the raw syngas;
- ICE intake and exhaust temperature;
- ICE in-cylinder pressure;
- water temperature in the heat recovery circuit;
- air mass flow rate at the gasifier and at the engine;
- water mass flow rate.

Woodchip is used for the characterization of the "baseline" configuration. A sample from the loading hopper is taken and analyzed with a thermo-balance to get the proximate analysis and carbon/hydrogen/nitrogen content for the ultimate analysis, according to current Unified European Legislation. The results are shown in Tables 2 and 3. These compositions are requested from the gasifier model in Thermoflex^{TM}, together with the pressure of gasification process, the equivalence ratio and the value of carbon conversion. The last two parameters are indeed unknown, so they are determined through a parametric analysis until the calculated composition and temperature of the raw syngas get similar to the experimental one. The actual composition of the syngas is in fact obtained by filling four laboratory bags by spillage downstream of the cooler and analyzed offline with a gas chromatograph. The final composition, in molar fraction on dry basis is compared with the composition calculated with the gasifier model. The comparison between the experimental and numerical results is shown in Fig. 9.

The part of the model relevant to the cooling and cleaning system and the heat recovery circuit is validated using experimental data obtained through thermocouples and pressure sensors mounted on the real plant in different strategic points [17, 18].

Table 2 Proximate analysis of woodchip on dry basis (db).

Parameter	Values	Method
Moisture	25%	
Ash	0.51%$_{db}$	UNI EN 14775:2005
Volatile matter	78.69%$_{db}$	UNI EN 14775:2005
Fix carbon	20.80%$_{db}$	UNI EN 14775:2005

Table 3 Ultimate analysis of woodchip on dry basis (db).

Parameter	Values	Method
Carbon	46.6%$_{db}$	UNI EN 15104:2011
Hydrogen	5.08%$_{db}$	UNI EN 15104:2011
Nitrogen	0.04%$_{db}$	UNI EN 15104:2011
Sulfur	0.015%$_{db}$	UNI EN 15289:2011 UNI EN ISO 10304-1:2009
Oxygen	47.76%$_{db}$	UNI EN 15104:2011
Chlorine	0.009%$_{db}$	UNI EN 15289:2011 UNI EN ISO 10304-1:2009

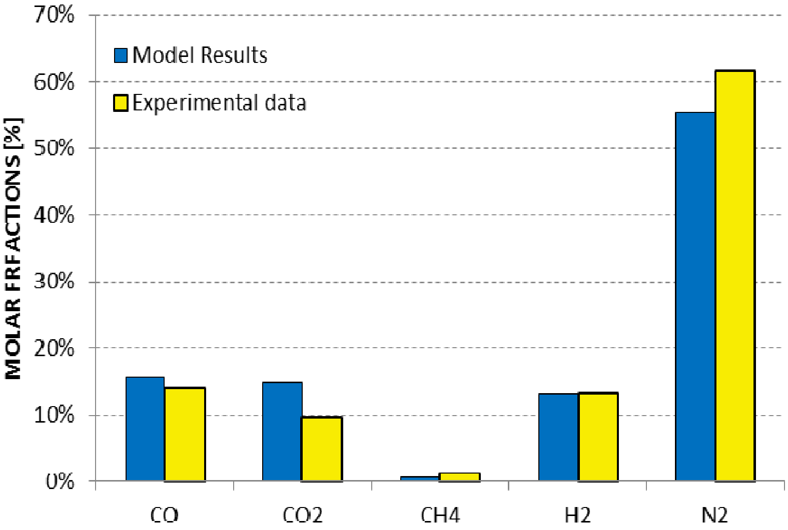


Fig. 9 Model results compared with experimental data for syngas composition.

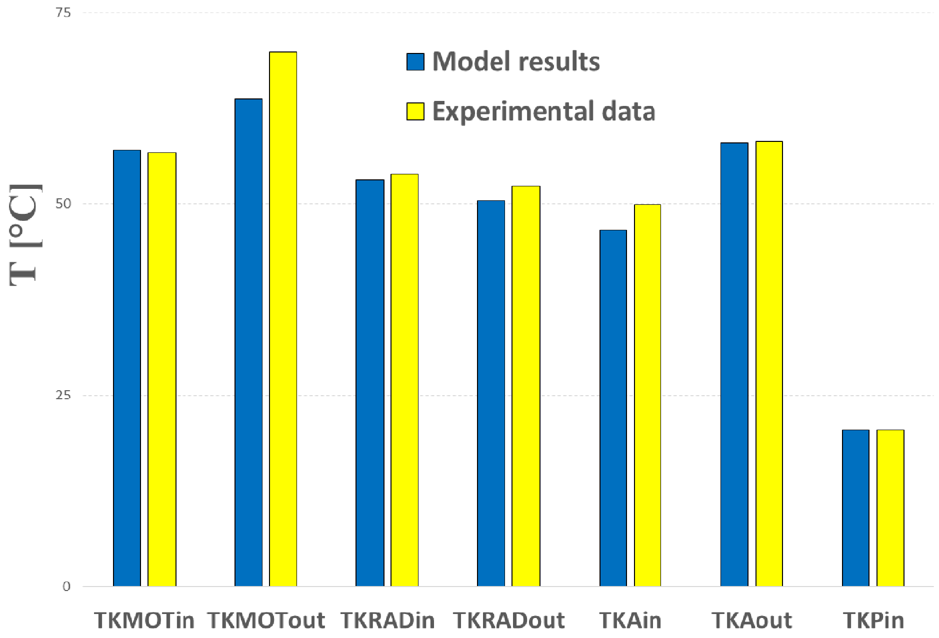


Fig. 10 Model results compared with experimental data for temperatures of the cooling water.

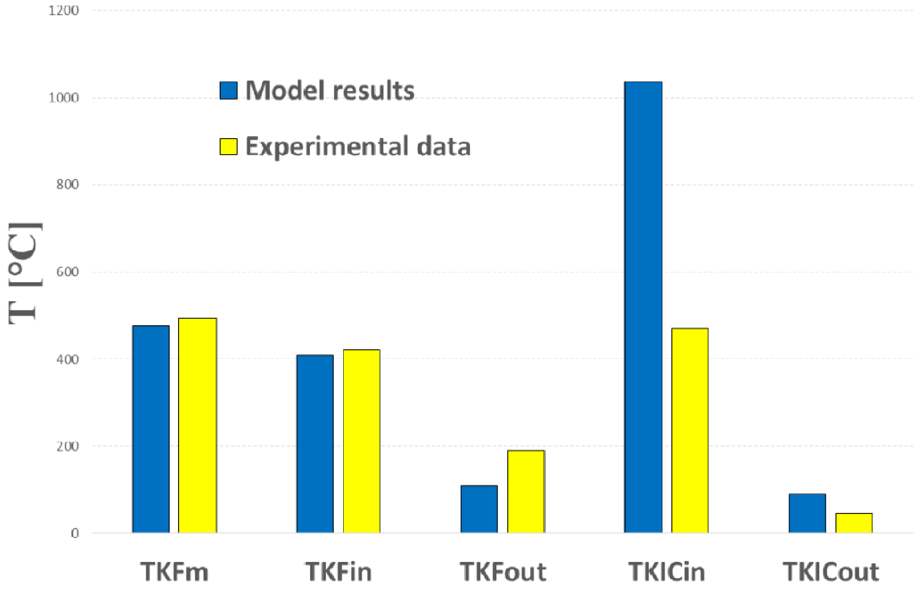


Fig. 11 Model results compared with experimental data for temperatures measured on the syngas line.

The thermocouples measures:

$T_{\mathrm{KFin/out}}$: inlet/outlet temperature of the ICE exhaust gases into and from the shell and tube heat exchanger;

$T_{\mathrm{KAin/out}}$: inlet/outlet temperature of water in the secondary circuit into and from the shell and tube heat exchanger;

T_{KPin}: inlet temperature of water in the secondary circuit into the plate heat exchanger;

$T_{\mathrm{KRADin/out}}$: inlet/outlet temperature of water in the primary circuit into and from the radiator;

$T_{\mathrm{MOTin/out}}$: inlet/outlet temperature of the engine cooling water in the primary circuit;

$T_{\mathrm{KICin/out}}$: inlet/outlet temperature of the syngas into the cooler;

T_{KFM}: inlet temperature of the exhaust gases into the reactor.

Average values of the effected measurements are used in first law balances and allow the tuning of the model thermal behavior with respect to measurements. Results are shown in Figs. 10 and 11.

The main difference between model results and experimental data is the net discrepancy regarding the syngas inlet and outlet temperature into and from the cooler (T_{KICin} and T_{KICout}). The reasons are two: firstly the real cleaning system of the plant consists of a reactor cyclone, a biological filter, a cooler and an engine cyclone, while in Thermoflex™ it is simply modeled with an heat exchanger that simulates the cooler action: each component of the cleaning section leads to a reduction of the temperature; then, the inlet value depends upon several variables such as the gasifier operating conditions. To give coherence to the model, T_{KICout} is imposed, to reproduce the real temperature conditions of the air syngas mixture before being delivered to the engine.

The 0-1D engine model validation requires instead a different approach. A spark plug pressure sensor is indeed mounted on the engine to get the indicated pressure cycle into the combustion chamber.

Five hundred cycles in various operating conditions are acquired to validate the numerical model. The spark timing and load are also varied to get a map as complete as possible. In this way it is possible to simulate the engine behavior under different operating conditions.

The curves in Fig. 12 show the comparison between the average pressure cycle measured in the first cylinder of the Vortec 3.0 ICE working at nominal value and the pressure cycle calculated with the 0D-1D model. As previously said, the combustion model is adjusted to the specific syngas composition by first evaluating the laminar flame speed through the Chemkin® code and then by introducing the needed parameters into the GT-Suite® environment. The shown curves represent the comparison between the overall pressure cycle and the well-captured agreement in about the engine closed valve period.

The link between the various sub-models of the CMD ECO 20 components is made by means of E-link, a Thermoflex™ tool that generates an excel file with the propriety of syngas produced in the reactor from which GT-Power takes the input parameters for the engine (composition of fuel, pressure and temperature).

7. Results and Discussion

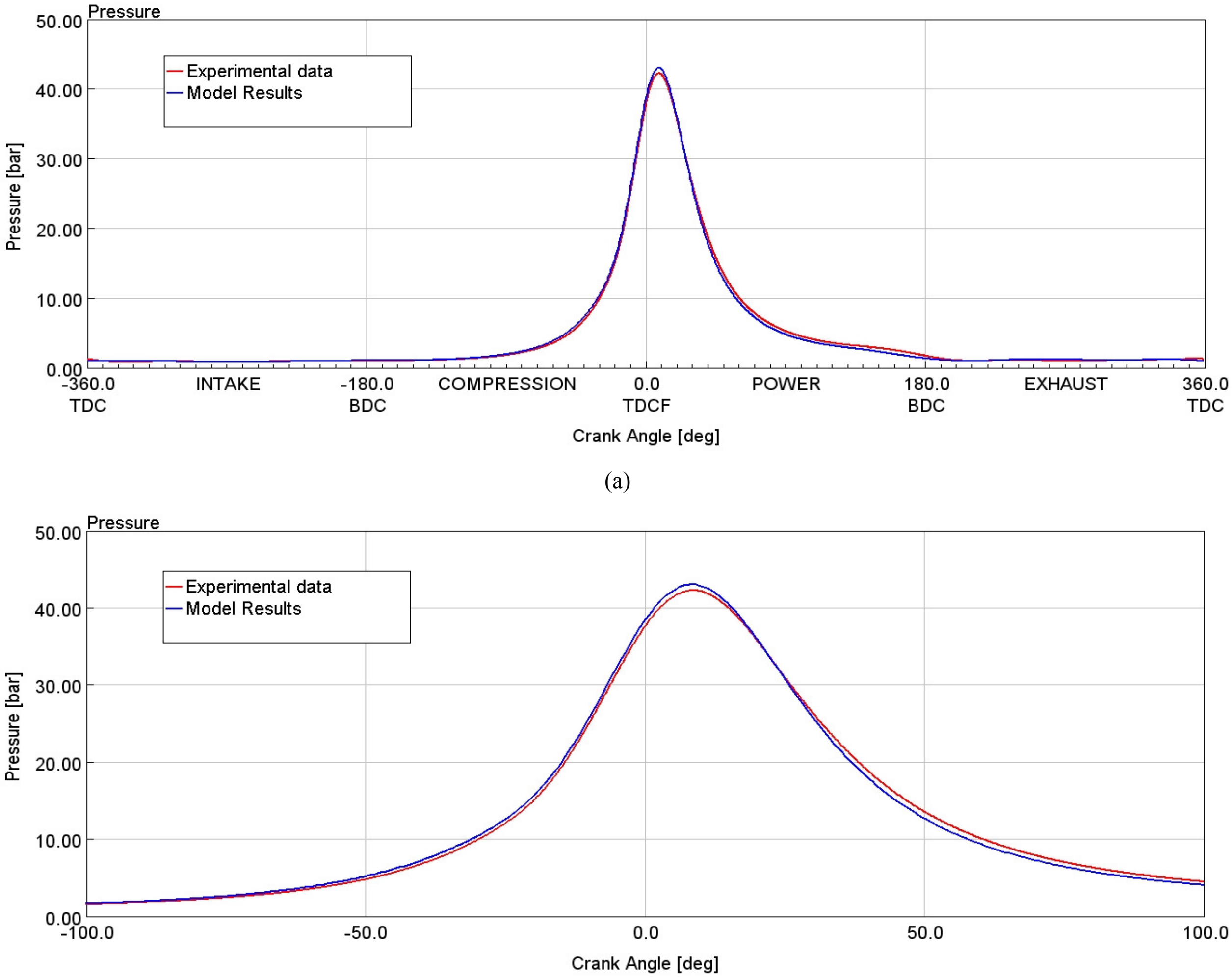
The whole CMD ECO20 model is used to perform parametric studies with respect to input parameter at the gasifier. The equivalent ratio and different moisture contents of the treated biomass are varied within intervals of interest and the same biomass is changed according to performed analyses of other materials.

7.1 Equivalence Ratio Effects

The equivalence ratio at the gasifier is defined as:

$$ER = \frac{Actual\ Air}{Stoichometric\ Air} = \frac{\frac{Air}{Fuel}}{\left(\frac{Air}{Fuel}\right)_{stech}} < 1$$

It is one of the most important parameters affecting the syngas quality. It defines the air used for the process and the quantity necessary under stoichiometric condition to reach complete oxidation of the combustible compounds. Clearly this parameter must be < 1 to avoid combustion. Fig. 13 shows the composition of the syngas from woodchips with respect to changes in ER between 0.1 and 0.6: when ER increases, the H_2 and CO_2 yield decrease while CO and N_2 increase; CH_4 also decreases with ER (the reaction of methanation requires low temperature, while the increasing of oxygen in input at the system raises up the temperature). For greater values of ER the behaviors of CO and CO_2 change: CO decreases and CO_2 increases that is an index of a partial combustion occurrence.



(a)

(b)

Fig. 12 Comparison between model results and experimental data relevant to the engine pressure cycle (a) and detail of the cycle during combustion (b).

In general, when ER increases, the syngas LHV decreases because the amount of combustible gases as CO, H_2, and CH_4 decreases. The relevant increase of this case, cold gas efficiency goes down due to the reduced lower heating value, as shown in Fig. 14.

The quality of the gas obtained from a gasifier strongly depends upon the value of ER. Lower values of ER ensure that the fuel is gasified rather than burned and the obtained syngas retains a larger share of combustibles and a higher LHV. However, an excessively low ER (< 0.2) results in several technologic problems, like incomplete gasification, excessive char and tar formation, risk that the process evolves into pyrolysis. Higher ER values allow a greater amount of oxygen to react with volatiles in the pyrolysis zone. Above ER = 0.23, phenols are nearly all converted and less tar is formed. This decrease is greater at higher temperatures. A higher ER reduces the tar and the quality of the gas as well. On the other hand, as already mentioned in the parametric study, a too high ER (> 0.4) results in an excessive formation of products of complete combustion, such as CO_2 and H_2O, at the expense of desirable products, such as CO and H_2 [5].

As a consequence of the LHV trend, the power generation by the considered mCHP system heavily changes. Its trend is not the same of LHV, as shown in Fig. 15. For small values of ER, mass flow rate of

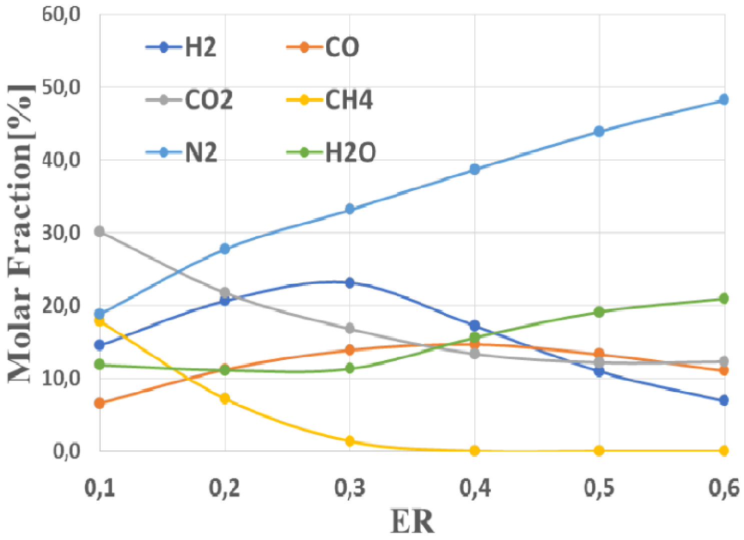


Fig. 13 Effect of ER on syngas from woodchips composition in terms of molar fraction.

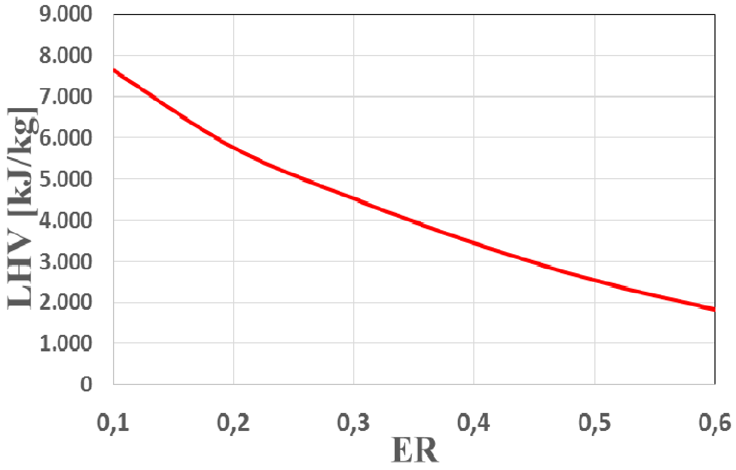


Fig. 14 Effect on gasifier ER on LHV of syngas from woodchips.

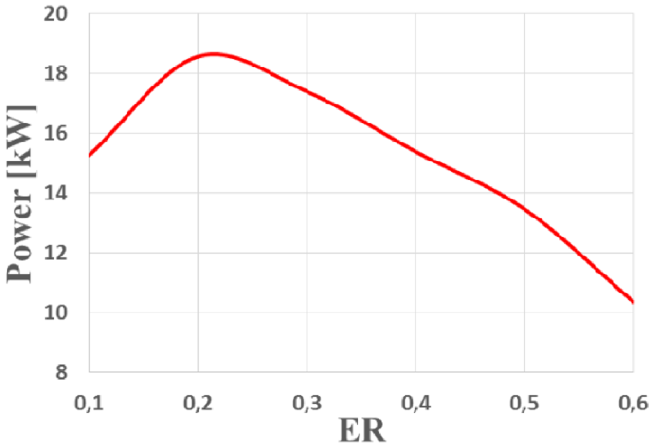


Fig. 15 Trend of mechanical power with ER.

syngas is very low and mixture burns more slowly, nullifying the advantage of a better LHV, canceled by a lower combustion efficiency. An optimal value of ER, therefore can be identified, that is a very interesting result of the present analysis. As this stays around 0.22, but, as previously said, technological problems arise for ER < 0.3, this last is assumed as optimal for the forthcoming analysis.

7.2 Biomass Moisture Content Effect

Typical moisture content of freshly cut woods ranges from 30% to 60%, and for some biomasses, it can exceed 90% (for example sewage sludge and organic fraction of municipal solid waste).

Each kilogram of moisture in the biomass takes away a minimum of about 2,242 kJ of extra energy from the gasifier to vaporize water. This energy is lost to the detriment of syngas LHV. This is the principal reason for the need of a preliminary drying before the biomass is fed to the gasifier.

The here performed parametric analysis, whose main results are shown in Fig. 16, clearly highlights that an increase of humidity causes a decrease in the LHV of the syngas. This is due to the combustion sub-process that is a part of gasification which has to proceed further when more water is involved in order to achieve the same process temperature.

In fact, the increase of the moisture content up to the to 40% slowly increases the H_2 content in the syngas, the CO_2 content is also increased, the CO content is decreased, and the gasification temperature of the producer gas is decreased, as shown in Fig. 17.

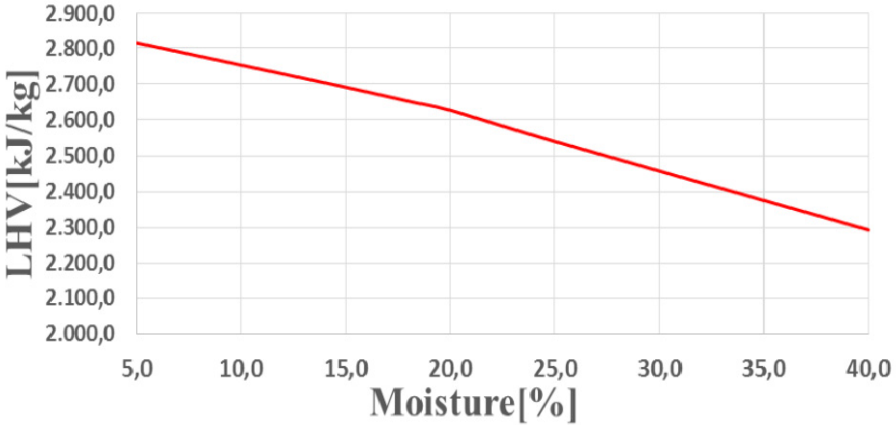


Fig. 16 Trend of raw syngas LHV with different moisture contents of the treated biomass.

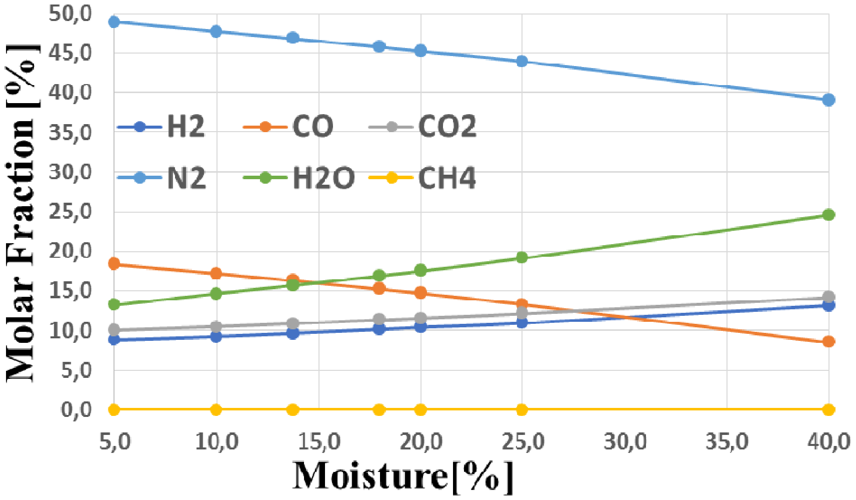


Fig. 17 Effect of moisture content on syngas composition in terms of molar fractions.

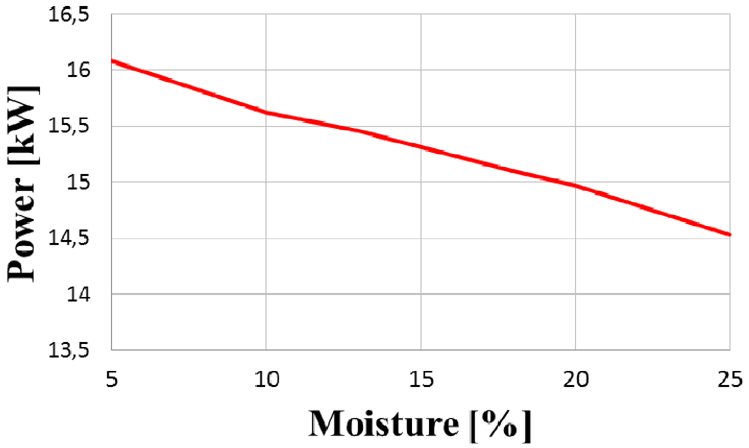


Fig. 18 Trend of mechanical power with respect to biomass moisture increase.

As a consequence of the LHV trend, the electric power generation of the CMD ECO20 system heavily changes. Its trend is in concordance with LHV as shown in Fig. 18. The analysis indeed must be stopped at 25% of moisture content because with greater values of initial moisture the air/syngas mixture does not undergo combustion in the engine.

The optimal value of biomass moisture for the maximum mCHP power generation is indeed theoretically equal to zero, although a completely dry biomass is known to not behave well under a real gasification process as technical problems arise, not suitable of being modeled within 0D approximations of the reactor. A value of the 10% is therefore considered in the following.

7.3 Optimization of Gasification Parameter

In conclusion, the better arrangement for the gasification parameters analyzed, considering also the real operating conditions, appears:

- ER = 0.3 (to be sure that the phenols are nearly all converted and less tar is formed);
- moisture content = 10% (that is the smallest value for a correct gasifier operation in a real plant).

The developed model, therefore, is run under these input parameters. Figs. 19 and 20 show a comparison between the baseline and the model results for the optimal controlling parameters in terms of syngas composition and LHV.

With the optimum syngas, a further analysis is carried out, to estimate the mechanical power as the ICE spark ignition timing is changed. Table 4 summarizes results and Fig. 21 shows the trend of brake power and brake torque as function of the spark advance.

It is clear that the engine operation must be optimized for every type of syngas. Changing spark timing from the value of 33 °BTDC (before the top dead center) of the baseline configuration, to 18 °BTDC, allows gaining about 13.6% of brake power, with a consequent improvement in energy efficiency, as the primary energy delivered to the engine remains unvaried.

7.4 Biomass Composition Effect

The analysis is an explorative one to evaluate the electric output of the system as different biomasses are considered.

In particular, the baseline biomass with the original ER at the gasifier, the same biomass with the optimized parameters (10% moisture content and gasifier ER = 0.3), fine woody biomass from maple and a biochar [19, 20] are considered. In Table 5 the ultimate analyses of maple and biochar are shown.

The simulation, done in the same condition for all the biomasses considered, gives the syngas composition shown in Fig. 22 and the syngas LHV reported in Fig. 23.

The influence of the different biomasses on power generation is quantified in Table 6. Results are not in

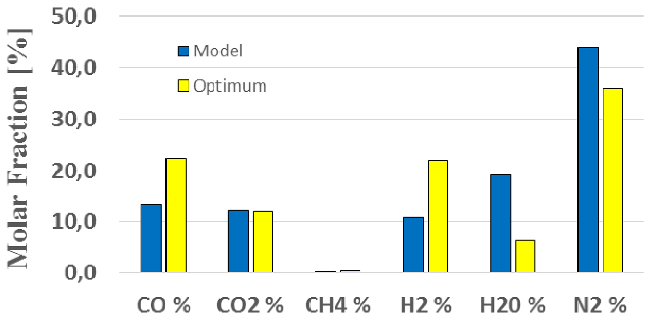


Fig. 19 Comparison of syngas composition between the baseline and the operation with optimal parameters.

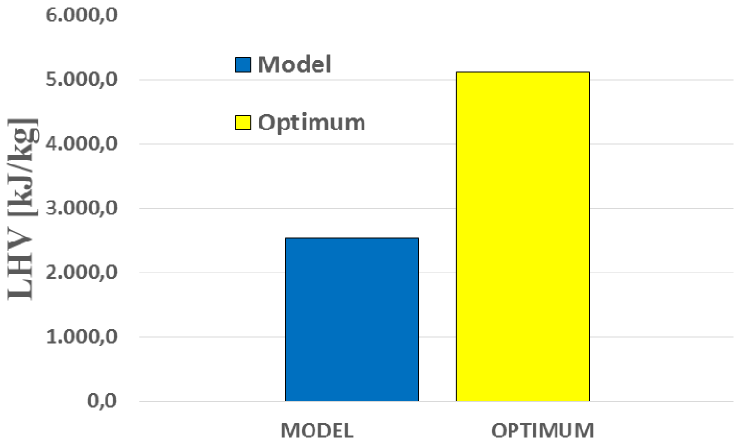


Fig. 20 Comparison of syngas LHV between the baseline and the operation with optimal parameters.

Table 4 Spark timing analysis results.

Spark (°BTDC)	Brake power (kW)	IMEP (bar)	$T_{Exhaust}$ (K)
43	15.93	5.44	815
38	17.43	5.84	820
33	18.85	6.21	829
28	20.05	6.51	843
23	20.94	6.73	862
18	21.42	6.82	888
13	21.35	6.78	921
8	20.58	6.53	957
3	19.12	6.10	1,004

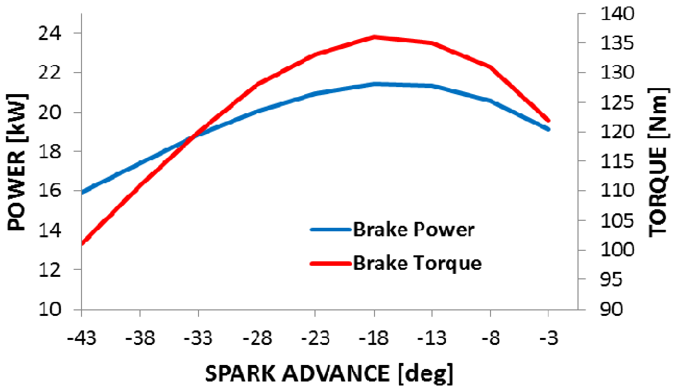


Fig. 21 Engine brake torque and brake power as a function of the spark advance.

Table 5 Ultimate analysis of maple wood and biochar.

	Maple	Biochar
Moisture (%)	8.40	7.00
Ash (%)	1.28	24.0
Carbon (%)	46.35	46.50
Hydrogen (%)	5.49	5.10
Nitrogen (%)	0.27	2.10
Oxygen (%)	38.2	12.79

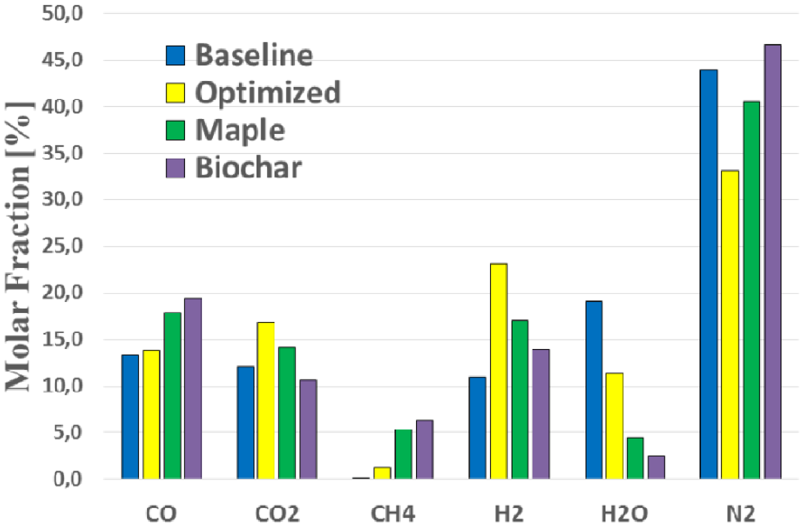


Fig. 22 Syngas composition produced by different biomasses.

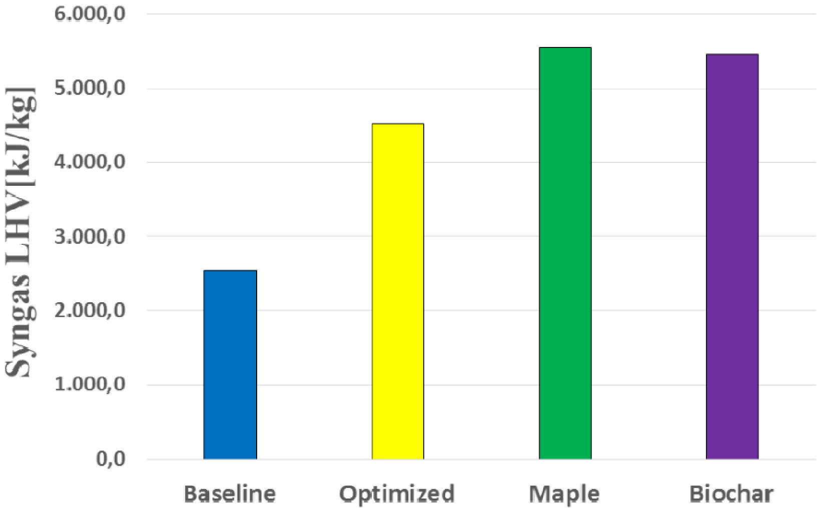


Fig. 23 LHV for syngas from different biomasses.

Table 6 ICE brake power calculated for different biomasses entering the reactor.

Biomass	Brake power (kW)
Baseline woodchips not optimized ER	14.53
Woodchips with 10% moisture	18.84
Maple	21.33
Biochar	21.71

agreement with expectations. Biochar, despite not having the highest LHV, is the one leading to the better performance. It should be noted that the spark advance used in the ICE is the same for all the used biomasses. The ICE is here not optimized, so it cannot be excluded that the syngas produced by maple, with a better ignition strategy, could give more power to the brake than the biochar, although the difference is indeed actually very low.

8. Conclusions

Gasification technology can be an interesting solution for energy production from renewable sources with respect to traditional combustion processes, due to the following aspects:

- cleaner and more efficient combustion of the released syngas;
- reduction the production of organic micro-pollutants as well as of NO_X and SO_X.

The first goal of the research activities in the field must be the elimination of the causes that hinder its development on a large scale. Several technological problems indeed exist, first of all the compatibility between the obtained syngas and ICE generally developed to be operated with traditional fuels as natural gas. The optimal operation of engines coupled with gasification plants requires a high quality standard fuel, but syngas quality not always is sufficient.

To study all the parameters that affect the optimal working of a coupled gasifier/ICE system, a numerical model of a micro-scale CHP commercial unit is presented. The modeled plant is composed of a gasifier, a syngas cooling system, an SI ICE with heat recovery system and an electrical generator.

The scheme of the gasifier, cooling system and heat exchangers for recovery from exhaust gas, is modeled thanks to experimental measurement and energy balance to quantify the flows in the various sections of the plant and to determine the syngas composition as resulting from biomass gasification.

A 0-1D ICE model is built thanks to measurements taken to define the geometrical characteristics. A proper model of combustion is customised to a varying composition syngas. This aspect is fundamental to gain predictive results able to give information about the combustion efficiency and, for the next future, for possible knocking occurrence and pollutant emissions evaluation.

The parametric analyses made in this work confirm the extreme sensitivity of the whole mCHP system to external inputs, like biomass kind, biomass moisture content or equivalent ratio at the gasifier. The ICE is operated under stoichiometric charge. The analysis on the effect of the ICE spark advance confirms the importance to well calibrate the engine as a function of the specific biomass treated in the gasifier.

The developed reliable numerical model allows analyzing any aspect of the process and enables a numerical optimization, useful for the setting of a whole plant governing parameters.

Acknowledgments

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