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Process simulation of a SOFC and double bubbling fluidized bed gasifier power plant

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ABSTRACT

The development of reliable fuel cells power plant based on renewable fuels stands out as one of the promising energy systems solutions for the future. Indeed fuel cells can increase the efficiency and the cleaning of the electrical energy production from renewable fuels. Process simulations of advanced power plants fed by low cost renewable fuels like biomass waste are a key step to develop renewable resources based on high temperature fuel cells applications. The aim of this work is to predict the component behaviour of a specific power plant mainly composed of a small indirectly heated gasifier and a Solid Oxide Fuel Cell (SOFC) and fed by chestnut coppice, waste available in great quantity in Central Italy, as well as in several other European regions. The plant's thermodynamic behaviour is analysed by means of the process simulator CHEMCAD© in which particular models for the SOFC and the gasifier have been developed in FORTRAN by the authors and then interfaced to commercial software. The results of the predictive model are presented and discussed, showing the possibility of an extremely interesting "carbon neutral" small plant configuration with high electrical and global efficiency exclusively based on the use of low cost renewable resources.
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1. Introduction

The realization of many international and national strategic plans, based upon renewable energy sources and hydrogen/fuel cells plans, demonstrates the increasing interest in the promotion and implementation of methods, technologies and processes for the development of sustainable energy systems [1–3].

In order to exploit biomass as a major source of energy in the power generation and transport sectors, there is a need for high efficient and clean energy conversion devices, especially in the low-medium range following the low energy density of this fuel [4,5].

Large installations, based on boiler coupled to steam turbine (or Integrated Gasification Combined Cycle power plant, IGCC), are too complex at small scale, meanwhile small biomass gasifiers coupled to Internal Combustion Engines, ICE, have low electrical efficiency (15–30%) and generally not negligible emissions [6].

High temperature fuel cells represent the most promising technologies for achieving higher conversion efficiency and reducing emissions especially at small scale. Due to its higher

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power density and operating temperature, Solid Oxide Fuel Cells (SOFCs) are considered as the major candidate for power generation and cogeneration units [7].

In the last years many studies have assessed operating conditions, system performance, potentials and limits of a variety of SOFC power plant including the hybrid Gas Turbine SOFC plant and the integration of SOFC systems with biomass gasification where the SOFC electrical efficiency, the total thermal efficiency and the total electrical efficiency can, ideally, reach the values of 42%, 38% and 62% respectively, based on the low heating value of the biomass [8–10].

This paper deals with a specific power plant configuration, based on a particular small indirectly heated fluidised bed gasifier, high temperature fuel cells (SOFC) and micro Gas Turbine (mGT). In particular the gasifier is based on UNIQUE concept. UNIQUE consists of a compact a gasifier integrating the fluidized bed steam gasification of biomass and the hot gas cleaning system into one reactor vessel, by means of a bundle of ceramic filter candles that operates at high temperature (800–850 °C) in the gasifier freeboard. Such configuration produce a syngas free of tar and sulphur compounds and allows for remarkable plant simplification and reduction of costs [11–13].

The analysis is based on process models that have been developed by the authors in earlier works [14–16] where they carried out process simulations of MCFC system integrated with biomass gasification and hot gas cleaning. Black-box and empirical models were used for the gasification process.

The plant's thermodynamic behaviour is analysed by means of the process simulator CHEMCAD©. The plant operation is optimized in terms of energy management, including cogeneration. The models for the SOFC and the gasifier have been developed in FORTRAN by the authors and then interfaced to the commercial software CHEMCAD©. Indeed different types of models can be developed, from complex fluid dynamics models, to simpler black-box or zero-dimension models, but to really predict the behaviour of a complex system like a biomass gasifier under different conditions the fluid dynamics models are the best developed models up to date [17].

Finally a sensitivity study of the power produced was carried out varying the moisture content in the biomass from 10 to 30%.

Regarding the error analysis, the mass and energy conservation principles are inherently satisfied by the software and the model, while the results are validated by comparing simulated with experimental data.

2. Power plant description

The proposed power plant mainly consists of a particular gasifier that produces a woodgas to feed an SOFC while the high temperature residual heat is used in a Capstone C15 mGT [18], to produce further electrical power.

Fig. 1 shows the CHEMCAD© plant flowsheet. The incoming biomass is gasified only by steam in the small indirectly heated fluidized bed gasifier (100 kWth). The steam is generated by the residual heat of the mGT exhausts. From the gasifier (Stream 1) a woodgas is obtained at 800 °C. The char and bed material are recirculated (Stream 2) in the burner of gasifier to produce the process heat. The woodgas is cleaned up from tars and particulate directly in the freeboard of the gasifier. This can be obtained by placing a bundle of catalytic ceramic candles in the gasifier freeboard. These candles convert tars by steam reforming and remove particulate at a temperature as high as the gasification temperature (800–850 °C). The cleaned woodgas is utilized in the SOFC module to produce the electrical power. The anode exhausts, still rich of H_2, CO and CH_4, are burned with residual char in the burner of gasifier, to produce the necessary heat for the gasification process. The hot flue gases from burner of gasifier at 950 °C (Stream 3) are exploited to heat the compressed air for the turbine, to obtain further power from the mGT.

In order to simulate the power plant SOFC and steam-gasifier specific models have been developed and described in the following paragraphs. The remaining components of the plant were simulated using conventional CHEMCAD blocks, in particular the catalytic reforming downstream gasifier was simulated by using a Gibbs reactor, while for the combustor of the gasifier a stoichiometric reactor was used.

3. Gasifier model

The gasifier model receives as input the pyrolysis products and calculates the woodgas composition. Indeed in fluidized bed gasifier the pyrolysis reactions can be considered as flash pyrolysis; the time necessary to reach the final products of pyrolysis can be neglected. For this reason, it was assumed that the fuel feeding the gasifier is that obtainable from pyrolysis of wood at the same operative conditions. The experimental results of Jand and Foscolo [19] were used in this study.

The products of pyrolysis are composed of CO_2, CO, H_2O, H_2, and CH_4, light and heavy hydrocarbons (tar) and char, as showed in Table 1.

The gasification reactions considered in this study are:

$$C + H_2O \rightarrow CO + H_2 \quad \text{(R1)}$$

$$C + CO_2 \rightarrow 2CO \quad \text{(R2)}$$

$$C + 2H_2 \rightarrow CH_4 \quad \text{(R3)}$$

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \quad \text{(R4)}$$

$$CO + H_2O\ ; \leftrightarrow CO_2 + H_2 \quad \text{(R5)}$$

$$C_{10}H_8 + 10H_2O\ ; \leftrightarrow 10CO + 14H_2 \quad \text{(R6)}$$

Napthalene have been used as tar representative.

Regarding the reactor fluid dynamics the Kunii and Levenspiel bubbling bed model [20] has been used. An outline of their model employed in this study is shown in Fig. 2.

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