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Investigations on an advanced power system based on a high temperature polymer electrolyte membrane fuel cell and an organic Rankine cycle for heating and power production

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ABSTRACT

Energy systems based on fuel cells technology can have a strategic role in the range of small-size power generation for the sustainable energy development.

In order to enhance their performance, it is possible to recover the "*waste heat*" from the fuel cells, for producing or thermal power (cogeneration systems) or further electric power by means of a bottoming power cycle (combined systems).

In this work an advanced system based on the integration between a HT-PEMFC (high temperature polymer electrolyte membrane fuel cell) power unit and an ORC (organic Rankine cycle) plant, has been proposed and analysed as suitable energy power plant for supplying electric and thermal energies to a stand-alone residential utility.

The system can operate both as cogeneration system, in which the electric and thermal loads are satisfied by the HT-PEMFC power unit and as electric generation system, in which the low temperature heat recovered from the fuel cells is used as energy source in the ORC plant for increasing the electric power production.

A numerical model, able to characterize the behavior and to predict the performance of the HT-PEMFC/ORC system under different working conditions, has been developed by using the AspenPlus™ code.

1. Background and scope

Strategies for the sustainable energy development are based on the efficiency improvement in existing energy systems, on the high efficiency technologies development and on the increase of the share of renewable energy sources.

Moreover, great attention is devoted to the promotion of the DG (distributed generation) because it allows to overcame some critical issues such as high emissions, transmission losses, long lead times for plant construction, and large and long term financing requirements.

In this contest, the fuel cell technology permits to match the promotion of the DG and the energy production with high efficiency and low emissions [1]. In particular, in the range of small-size power generation, PEM (Polymer Electrolyte Membrane) fuel cells offer a promising, possibly green, alternative to traditional power sources and other fuel cell types without air polluting issues [2–14].

The main critical issues of PEM fuel cells are the water management and the purity of the feeding fuel (pure hydrogen or syngas with CO content less than 10 ppm).

At high current densities, liquid water, the electrochemical result of combining hydrogen and oxygen at a temperature below 100 °C, accumulates at the cathode due to the ORR (oxygen reduction reaction). In this condition (cathode flooding), about one-third of the electrode surface area may not be used with a decreasing of the fuel cell performance [14].

As it is known, PEMFCs have to be fed with high purity hydrogen gas, but pure hydrogen is unlikely to be the fuel source in the near term, due to technical and economic considerations in production and storage. Thus, in order to overcome the lack of hydrogen infrastructure, the PEMFC can be operated with syngas produced by reforming conventional fuels such as natural gas, available in most

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metropolitan households. However, this reformate gas contains small amounts of CO (carbon monoxide) which poisons the platinum anode catalyst. This limit can be get over by increasing the PEM fuel cell operating temperature at values higher than 100 °C (High Temperature PEM fuel cell, HT-PEMFC) because the adsorption of CO onto the catalyst sites diminishes with the temperature rising [15].

Therefore, in the last years, a great attention has been addressed to the research and the development of membrane materials such as PFSA (perfluorosulfonic acid) membranes and polybenzimidazole-based (PBI) membranes [16–18], which allow to operate at temperatures of about 120–180 °C.

The HT-PEMFCs require cell voltages of 0.7 V to achieve system efficiencies higher than LT-PEMFCs (Low Temperature PEM fuel cells), but their performance are currently still low [17]. In order to obtain system efficiencies higher than 40%, research efforts have been made to improve fuel cell components performance (i.e. membrane and electrode).

From a system-level point of view, an efficient strategy for enhancing the fuel cell system performance is to recover the "*waste heat*" to produce or thermal power (cogeneration systems) or electric power by means of a bottoming power cycle (combined systems).

Because the heat from the HT-PEMFC is available at low-moderate temperature (150–180 °C), the bottoming power cycle can be based on the ORC (organic Rankine cycle) technology that has often been applied for power production from low-grade heat source [19,20]. The ORC operates in a similar way to the steam Rankine cycle, but uses an organic compound instead of water as working fluid. As many organic compounds have a lower boiling temperature and a higher vapor pressure than water, the low-temperature waste heat recovery is favored [19,21] and the expansion ends in the superheated region, avoiding the erosion of turbine by wet steam [22].

The selection of the organic working fluid is a crucial aspect because it must have optimum thermodynamic properties and also satisfy several criteria, such as being economical, non-toxic, non-flammable and environmentally friendly [19,23]. Therefore, several research papers focus on the optimization criteria to define the optimal working fluid by considering different aspects like thermal efficiency, exergy efficiency and cost effective optimum design [24].

The waste heat recovery by means of the ORC systems has been studied and applied to different types of systems (solar thermal power, geothermal power, industrial waste heat, engine exhaust gases, domestic boilers), but few studies deal with the integration with PEM fuel cell power units [25,26].

Thus, in this work an advanced integrated power plant HT-PEMFC/ORC, called AFCOR (Advanced Fuel Cell and ORC), has been defined and analysed.

The AFCOR system is designed and sized for a stand-alone residential utility, so it has to satisfy the thermal and electrical energy demands. Thus, it can work in: i) CHP (combined heat and power) operation mode; ii) electric generation operation mode.

In the first case, the electric load is satisfied by running the fuel cell system and the available heat is used to cover the thermal energy demand; in the second one, the heat from the fuel cell is recovered by means of the ORC system to increase the electric power production.

A numerical model, able to characterize the behavior and to predict the performance of the HT-PEMFC/ORC system under different working conditions, is developed by using the AspenPlus™ code. The model has allowed to define the optimal operating parameters of the ORC system by considering the techno-economic constraints linked to both the integration with the fuel cell system and the components availability.

2. Plant configuration and description

The AFCOR system consists in the integration between a HT-PEMFC system, fed by natural gas, and an Organic Rankine Cycle that recovers the heat from the fuel cell cooling system to generate electrical power. In Fig. 1 the system layout is shown. It can be noted that there are two main units: i) the HTPS (high temperature power section) and ii) the LTPS (low temperature power section). The HTPS is formed by 10 power modules and each of them is a micro-cogeneration unit in which two HT-PEMFC stacks are fed by a natural gas steam reforming unit [12].

The LTPS consists of three heat exchangers (EVA, ECO, REGEN), an expander and a condenser.

3. System modeling

The AFCOR system is simulated by a thermo-chemical and electrochemical model developed by using the AspenPlus™ software package. The numerical model, consisting of independent sub-models, has a modular architecture that facilitates the integration between each unit according to the system operation mode. In this section each sub-model is described and detailed.

3.1. High temperature power section

The HTPS consists of 10 power modules and each module is the power unit studied in Ref. [12], able to satisfy the energy requirements (electric and thermal energy demands) of a residential utility. The power module, based on two HT-PEMFC stacks fed by a natural gas steam reforming unit, is designed to supply a maximum electric power of 2.5 ± 0.2 kW.

Fig. 2 shows the flowsheet of the power module. The reforming unit is a natural gas steam reforming system. In order to convert the fuel in a hydrogen rich stream with high conversion efficiency, the reforming process is carried out in two steps: i) a high temperature endothermic step that takes place in the SR (steam reforming reactor) in which the hydrocarbons are converted into a gaseous mixture of H_2, CO, CO_2, and unreacted H_2O; ii) a low temperature slightly esothermic step that occurs in the WGSR (water gas shift reactor) in which CO is reacted with H_2O towards H_2 and CO_2.

The heat required for the steam reforming reaction is supplied by a CB (catalytic burner) fed with the natural gas and the anodic exhausts from the fuel cell stacks. The heat recovered by the syngas cooling in the heat exchangers HEX1 and HEX2 allows to generate the steam needed for the reforming reactions, whereas the cathode off-gas, which has a high enthalpy content, is used to pre-heat the combustion air for the catalytic burner (HEX3). Furthermore, because no humidification of anodic and cathodic flows is needed, the water content in the reformate is removed by means of a WKD (water knock-out drum).

The critical operating parameters of the reforming unit are the steam reforming temperature, and the steam to carbon ratio S/C, defined as the ratio between the steam and the fuel mole flow rates feeding the reforming reactor. The choice of these parameters affect significantly the thermal efficiency of the process because higher values of S/C move the reforming reaction to the products and, at the same time, avoid the carbon deposition on the catalyst surface which would drastically reduce the system performance. However, high values of S/C increase the heat required to sustain the steam reforming reactions, with negative consequences on the overall system efficiency, unless an appropriate thermal recovery of the heat flows within the system is performed [27,28].

The stack consists of 55 high temperature PEM fuel cells with a PBI-based membrane (polybendimidazole material doped with phosphoric acid) operating at 160 °C.