Propulsion and Trigeneration by Fuel Cell: an Eco-friendly Camper van

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Abstract: - Among the several systems for energy production, fuel cells in a trigenerative arrangement are certainly some of the most attractive. They, in fact, could simultaneously supply both thermal and electrical power and, if connected to a system of absorption, they allow environment conditioning by using their discarded thermal energy. In the present paper, the results of an energetic and environmental analysis of low power fuel cell systems, in terms of some meaningful parameters, such as the global efficiency, the exergetic efficiency and the environmental impact index. In particular, as an application to a real case the feasibility to satisfy the energetic requirements of a camper van, has been considered, not only in terms of energetic satisfaction of the cab but also in terms of propulsion.

Key-Words: - Energy saving, Environment, PEMFC, PAFC, Trigeneration

1 Introduction

The problem of polluting substances, generated largely by industries, motor vehicles and heating plants, has assumed troublesome dimensions; the greenhouse effect, climatic imbalance, the overheating of the atmosphere are phenomena that must absolutely not be neglected, but that indeed demand immediate action. The alternative to this situation is to address research towards less polluting and if possible renewable energy sources that can replace the traditional systems of energy production. In this context, thanks to its high energy content, hydrogen can be very important even though there are problems of storage and management owing to its notable dangerousness. Jointly with fuel cell technology [1, 2], by which electrical power is produced through an electrochemical process, yielding warm water as a by-product, they assume an important role in the international energetic panorama. In this paper, the feasibility of realizing a vehicle for camping with low environmental impact is investigated, it employs fuel cells as propellent and generator of electrical, thermal and cooling power. The prerogative that would make this kind camper very attractive, in the context of energetic and environment rationalization, is the use of two fuel-cell systems. The first one for the propulsion and the second in a trigenerative arrangement in order to make the camper van independent in terms of thermo-electrical requirements, also in areas different from those where the vehicle can be externally fed. In fact, an opportune management of the thermal energy, in this case, through an absorption system, produced as fuel-cell system waste, concurs to supply the camper van cab properly produced electrical power, the necessary energy for environmental heating-cooling and also for the sanitary warm water. Therefore, an energetic and environmental analysis of the aforesaid systems was carried out, in the low-power field, in terms of some parameters such as the global efficiency, the exergetic efficiency and the environmental impact index.

2 Energy Analysis of a trigenerative System

In order to estimate the goodness of the trigenerative system some parameters taken out from [3] were elaborated ad hoc for the energetic evaluation.

The energetic system is analyzed by splitting thermal power into one part necessary to produce sanitary warm water and heating, and into another part necessary to the absorption system for the production of the demanded cooling energy from the air conditioning. The first meaningful parameter taken into consideration is the exergetic efficiency of the trigenerative system (η_{ex}^{TRIG}), given by equation (1):

$$\eta_{ex}^{TRIG} = \frac{Exergia_{output}}{Exergia_{input}} = \frac{P_{CH}^{GasP} + P_e + \alpha P_t\left(1 - \frac{T_o}{\bar{T}_{SC}}\right) + (1-\alpha)P_t\left(1 - \frac{T_Y}{T_R}\right)}{P_{CH}^{fuel}} \qquad (1)$$

where:

P_{CH}^{GasP}, exergetic content of the gas pollution [kW];

P_{CH}^{fuel}, fuel exergetic content [kW];

P_e, electrical power [kW];

P_t, thermal power [kW];

α, thermal power fraction for hot water and heating production;

$\left(1-T_o/T_{SC}\right)$, Carnot factor of the heat exchanger for hot water and heating production;

$\overline{T_{SC}}$, heat exchanger average temperature [K];

T_o, reference temperature (292 K);

$\left(1-T_Y/T_R\right)$, Carnot factor of the water-air heat-pump for the summer air-conditioning;

T_Y, reference temperature for air-conditioning [K], (assumed equal to the average temperature of the environment to be air-conditioned);

T_R, temperature of the hot source [K] (assumed equal to the temperature of the water in the accumulation boiler).

This first parameter takes into account the exergetic content of the system emissions, the produced electrical and thermal power opportunely weighed by the Carnot factor of the heat exchanger for the sanitary warm water production. This factor in its turn is a function both of the average temperature of thermal exchange and the reference temperature of the water. In addition, the exergetic efficiency is a function of the Carnot factor of the heat pump which in its turn is a function of the reference temperature for the conditioning, assumed equal to the average temperature of the environment to be air conditioned. In equation (1) α represents the fraction of thermal energy directed to both the section for the sanitary warm water production and the heating system, while its complement to one represents, obviously, the thermal energy destined to the absorption system for the eventual cooling.

The efficiency of the trigenerative system (η_{ex}^{TRIG}) is defined, starting from the assumption that the thermal and cooling powers of the system are produced separately and given in electrical terms through a conventional electrical efficiency (η_e^*) equal to 0.38 (as stated by the Italian Energy Authority); the trigenerative efficiency is expressed as:

$$\eta_{TRIG} = \frac{P_e + \frac{P_C}{\eta_t}\eta_e^* + \frac{P_f}{\eta_t}\frac{1}{COP}\eta_e^*}{P_{fuel}} \qquad (2)$$

where:

η_t, thermal efficiency of the energetic system;

P_C, thermal power for heating and warm water production [kW];

P_f, thermal power for air-conditioning [kW];

P_{fuel}, fuel power [kW];

COP, coefficient of performance of the heat-pump.

Therefore, the fraction of the saved fuel (FCR) of the trigenerative system is defined, in order to stress the saving, in terms of fuel consumption, with respect to the separate production of the several typologies of energies; this factor can be expressed from equation (3) in which η_t^* represents a conventional thermal efficiency, in this case, equal to 0.80 (as stated by the Italian Energy Authority):

$$FCR^{TRIG} = \frac{\left(\frac{P_e}{\eta_e^*}+\frac{P_C}{\eta_t^*}+\frac{P_f}{\eta_t^*}\right)^{CONV} - \left(\frac{P_e}{\eta_e}+\frac{P_C}{\eta_t}+\frac{P_f}{\eta_t}\frac{1}{COP}\right)^{TRIG}}{\left(\frac{P_e}{\eta_e^*}+\frac{P_C}{\eta_t^*}+\frac{P_f}{\eta_t^*}\right)^{CONV}} \qquad (3)$$

where:

η_e is the electrical efficiency of the system and the apexes TRIG and CONV are for trigenerative and conventional, respectively.

Both the two more traditional indices used for the classical evaluation of the cogenerative systems, i.e. the fuel utilization factor (FUC) and the energy saving index (IRE), were also considered. Equations (4) and (5) give these indices:

$$FUC^{TRIG} = \eta_e + \eta_t + \frac{P_f}{COP}\frac{1}{Q_{fuel}LHV} \qquad (4)$$

$$IRE^{TRIG} = \left(1 - \frac{Q_{fuel}\cdot LHV}{\frac{P_e}{\eta_e^*\cdot p_{grid}} + \frac{P_f+P_C}{\eta_t^*}}\right)\cdot 100 \qquad (5)$$

where:

Q_{fuel}, trigenerative system fuel flow, [kg/s];

LHV, lower specific heat of the feed fuel, [kJ/kg];

p_{grid}, loss transmission factor.

3 Environmental evaluation of energy systems

For a more complete energetic analysis of both the trigenerative and propulsive systems, in this paper an index of the environmental impact (I_{amb}) [4] is proposed. The aim is to transform the produced polluting substances in terms of carbon monoxide (CO) and nitrogen oxides (NOx) equivalents and to estimate the environmental impact of the considered energetic systems with the following equation (6):

$$I_{amb} = \sum_i p_i \cdot Q_i \qquad (6)$$

where:

Q represents the emitted quantity of the polluting substances, reported in table 2 and expressed in [kg_Q/kWh];

p is the weight, expressed in $\frac{kg(CO+NO_x)_{eq}}{kg_Q}$, depending on the quantities of the polluting substances and calculated by the:

$$p = \frac{CO}{X} * i_1 + \frac{NO_x}{X} * i_2 \qquad (7)$$

where:

CO and NO_x represent the limit values of this polluting, [kg/year];

X is the limit value of the considered polluting substance, [kg/year];

i_1, i_2 are the percentages in volume of CO and NO_x emitted from the considered energetic systems, (fuel-cell system composed of a stack and reformer section, or diesel engine).

The unit of measure of I_{amb} is $\frac{kg(CO+NO_x)_{eq}}{kWh}$.

It is important to stress that the polluting CO and NOx are predominant in the emissive propulsive computation.

4 Application to a camper van

The camper van investigated in this paper is the Mondial 62L model of Carthago, it is equipped with a 2.8-litre and 4-cylinder diesel engine with a, distributing power of 108 kW. The aim is to make the camper van completely independent, that is, able to satisfy all the passengers requirements in terms of electric, thermal and cooling energy, also when the vehicle is not parked in an appropriate camping area, where it can be connected to the electrical system. With regard to the propulsion, two cases can be distinguished, i.e. the case in which the propellant is the diesel engine of the vehicle and the case in which a fuel-cell system with polymer electrolyte is used, this type being the more consolidated technology for the applications in the field of the traction [5, 6]. A fuel-cell system of the PEMFC type, electrolyte polymer fuel cell or of the PAFC type, acid phosphoric fuel cell, to feed the passenger compartment appliances. In particular, because the consumption of the services of the camper van (consisting of the appliances, the warm or cold air production and the sanitary warm water production) are not greater than the consumptions of an ordinary home, for the analysis reported in this paper, these latter consumptions were assumed.

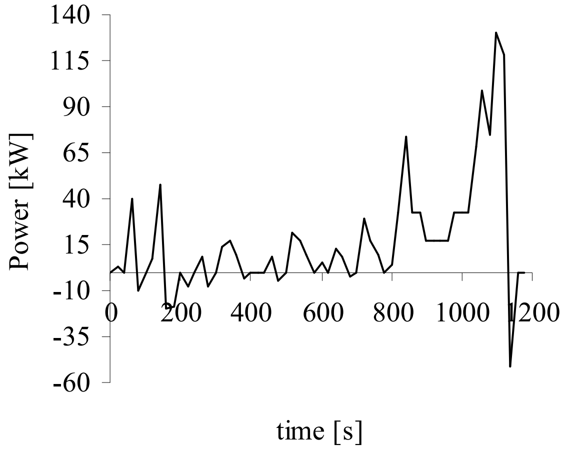

Fig. 1 Variation of the power needs at the wheels during a cycle.

In any case, the feeding of the fuel cells for both systems is carried out with natural gas for which a reforming section is considered in the vehicle. From the point of view of the traction, the action of the camper van is considered in the course of a cycle ECE15+EUDC ("European Cycle Emission" used when the city use of the vehicle is supposed, and "Extra-Urban Driving Cycle" used when an extra-city use of the vehicle is supposed). In Figure 1, the power demanded from the propellant is reported, while the power distributed from the stack during the cycle is reported in Figure 2.

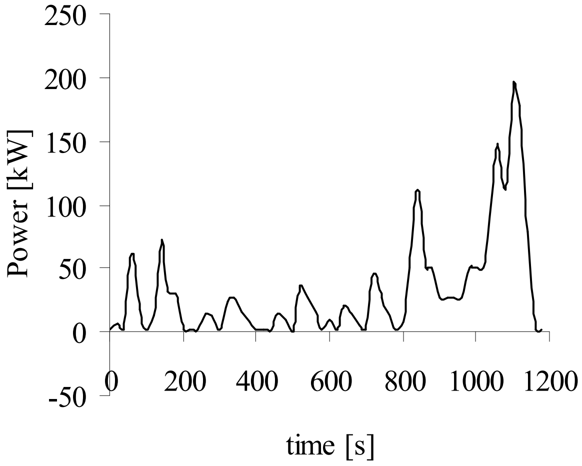

Fig. 2 PEMFC supplied power for cycle.

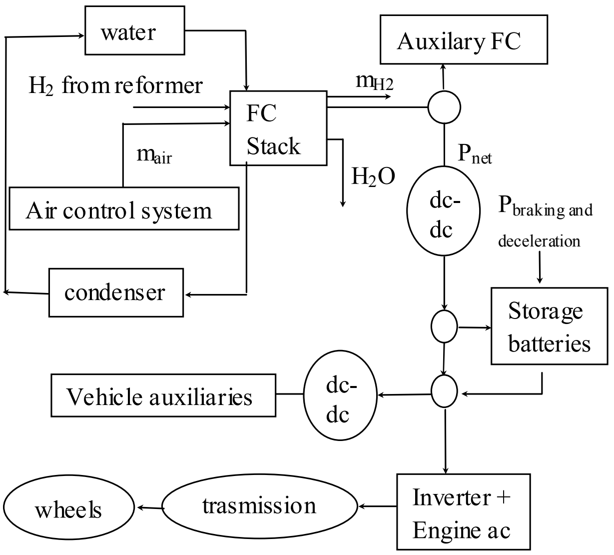

Fig. 3 Schematic representation of a Fuel Cell propulsion system.

The plant model adopted considers an electric power lung, as illustrated in Figure 3, consisting of a system of electrical accumulators whose stored energy is exploited in the starting stage, in order to satisfy the demand for energy during the temporal interval between the moment in which the vehicle is started to the moment in which the primary fuel is transformed into hydrogen in the reformer and the latter into electric power in the stack.

The system of accumulators is used when there are peaks of demand for electric energy, because, as known [7], the reformer is not able to follow the demand for the propellant, and also to recover the energy generated in the deceleration and braking phase. The flow of hydrogen generated from the reformer is constant [8], so the surplus energy demanded from the electric motor fed by the fuel-cell system is supplied from the accumulators. The thermal energy produced during the propulsion, is used inside the same system in the section of the fuel reformer.

As previously illustrated, a second fuel-cell system is considered for feeding the services in the vehicle, in particular a comparison between a PEMFC system and a PAFC system was carried out. The thermal energy produced as primary process waste from electric power production, is split into a quota used for producing sanitary warm water and necessary for the winter heating of the vehicle and the quota for the summer conditioning. In Table 1, the number of appliances and electrical accessories with the corresponding absorbed electrical power are reported.

The schematic representation of the feeding network of the services of the camper van is reported in Figure 4. The network provides all the components necessary to the energy for reaching the consumers with the demanded voltage and frequency. Moreover, a system of storage cells allows storage of surplus electric power, in order for it to be used when required.

Unit	number	Power W
Neon lights	11	6
	2	12
	1	22
Fan	1	45
	1	14
Fridge 135 l	1	85
15” TV	1	39
Radio	1	35

Tab. 1 Appliances and electrical accessories of the camper van.

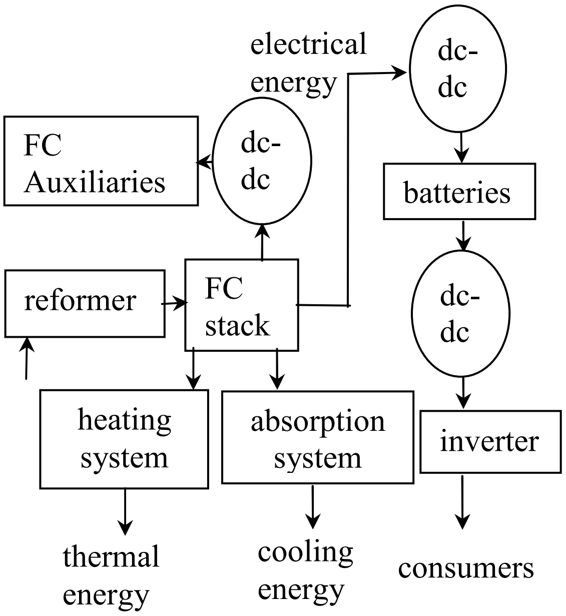

Fig. 4 Fuel cell system.

The thermal and cooling requirements, with regard to the air conditioning, are satisfied through an absorption system [9]. It consists of a water/air heat pump whose fluid carrier is the fuel-cell cooling system circuit water, which allows the thermal recovery of the waste heat deriving from the emissions produced by the reformer and by the warm water of the electrochemical process. A 100 liter boiler is proposed for sanitary warm water production. Inside the boiler a coil is covered with water that recovers waste heat, so as to guarantee a temperature in the boiler of approximately 45 °C (stand point temperature). Moreover, the system provides for electric integration in the storage boiler, which starts functioning when the heat recovered is insufficient to maintain the stand point temperature, effectively rarely used, established for the boiler and governed by the regulations relative to low-temperature heating systems, such as that installed in the vehicle. In Figure 5, the electrical, thermal and cooling requirements for a representative day are reported, in the case when the camper van operates in summer, winter or intermediate season.

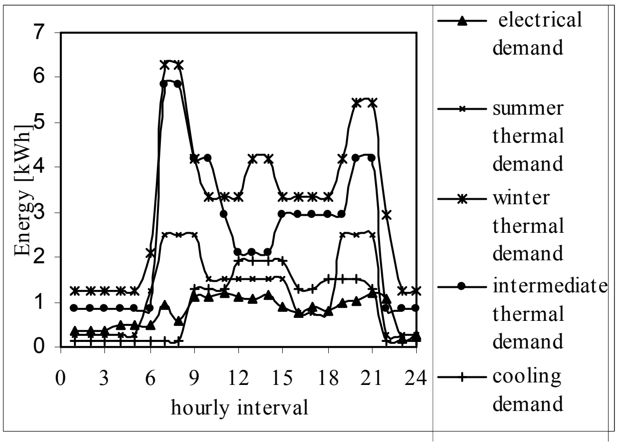

Fig. 5 Electrical, thermal and cooling demands for day.

From Figure 5 it can be noted how the electrical requirements are constant during the seasons, the electrical absorption is not, in fact, dependent on the environmental conditioning and heating.

5 Results analysis

The fuel-cell systems were designed for providing the internal electrical and thermal requirements of the camper van; therefore the energetic parameters introduced in the previous sections were determined. With regard to the propulsion, the environmental impact index was estimated for the propulsion system presented and then it was compared with the index characterizing the conventional propulsive system. For both the two fuel-cell systems the produced powers (electrical, thermal and cooling) were estimated, as can be observed in Figures 6 and 7, adopting the pursuit of the electrical load. Electrical production was increased, in part with the aim of satisfying the possible insufficiency of thermal energy, which can be verified, in particular, during the winter when the thermal energy requirements are more consistent both for heating and sanitary warm water production, but especially for accumulating electric power during the cell operating period, considering the possibility of turning it off in that period of the day the energetic demands are minimal.

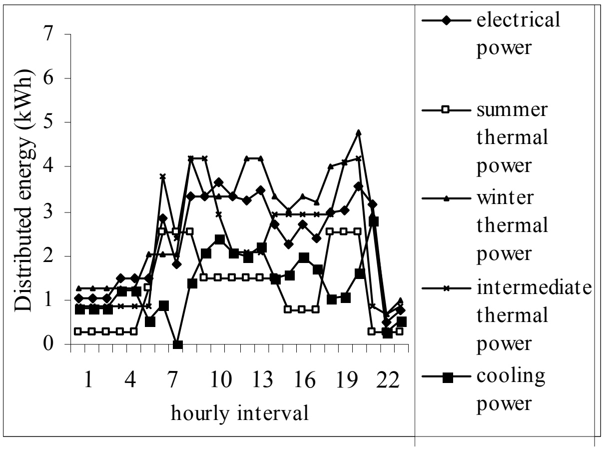

Fig. 6 Energy supplied by a PEMFC system.

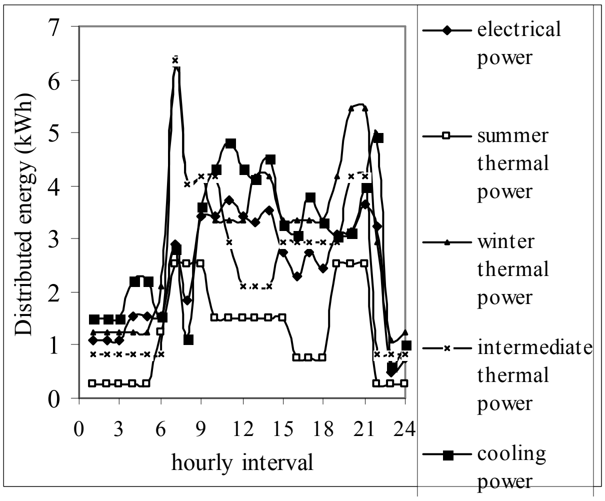

Fig. 7 Energy supplied by a PAFC system.

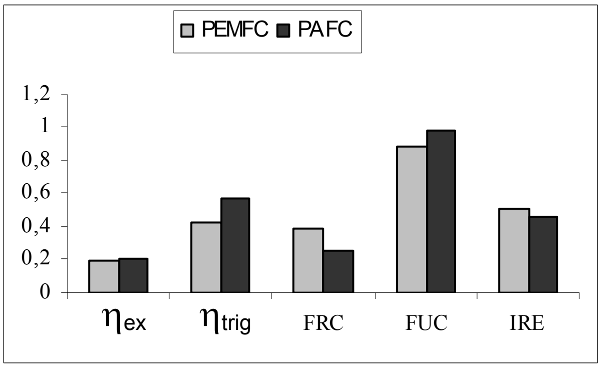

Fig. 8 A comparison of PEMFC and PAFC systems.

To face this increment, the electric energy produced in surplus is accumulated in an appropriate system constituted of recognized batteries with which the vehicle itself is equipped for emergencies. The system is able to release the accumulated energy during the time bands in which the system is turned off.

From Figures 6 and 7 it can be noted that both the fuel cells give good results on the three representative days, summer, winter and intermediate season, considered in the analysis, because they follow the variation of the demanded load very well.

Considering the parameters analyzed for the two fuel-cell systems, it can be observed from Figure 8 that with regard to the saved fraction of fuel, the lower value of the PAFC system is due to the greater flow of fuel required from this system, for the same distributed electrical power regarding the PEMFC. Consequently, as far as the fuel utilization factor is concerned, the higher value of the PAFC is due to the greater thermal efficiency characterizing these systems. As can be observed from Figure 8, the parameters for the two typologies of fuel cells considered in this paper are comparable.

pollution	CO_2	CO	SO_X	NO_X	COV
Limit Value [kg/year]	100 $x10^6$	500 $x10^3$	150 $x10^3$	100 $x10^3$	100x 10^3
Reformer [kg/kWh_f]	186	0,16	-	0,85	0,48
Diesel Engine [kg/kWh_f]	180	0.872	-	0.930	0.436
PEMFC [kg/kWh_f]	-	0,011	-	0,016	0,002
PAFC [kg/kWh_f]	-	0,008	-	0,007	0,002

Tab. 2 Gas pollution emissions and legal limits.

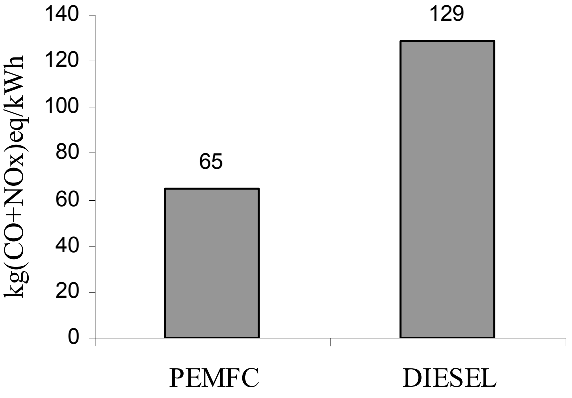

Fig. 9 Environmental impact index.

In terms of the environmental impact index, as can observed from Figure 9, the comparison of the polluting substances emitted from the considered energetic systems and propellent with the limiting values established by law reported in Table 2, shows a drastic reduction of about 50% in the atmospheric polluting by the cell with respect to conventional engines.

6 Conclusions

Analyzing the results obtained it is possible to point out how both the typologies of fuel-cell systems can be successfully used, in both energetic and environmental terms, in a trigenerative arrangement. From the values of the environmental impact index these systems seem to be able to satisfying the requirements of the camper van with a low production of atmospheric pollution, moreover, the adoption of these systems makes the camper van completely autonomous, also in the absence of connection to mains electricity in camping areas, indeed, the low emissions from the system itself can be added to the non-consumption of mains electricity. Even though in this paper no economic analyses are carried out, it must be underlined that if the fuel cells are not sponsored by suitable energy policies, their commercial costs, currently prohibitive, will continue, however, to make them non-competitive compared with the most mature conventional systems.

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