Systems' optimization: achieving the balance

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Abstract

Fuel cells for stationary power generation applications are being pursued on a large scale worldwide in an effort to achieve commercialization before the turn of the century. Some aspects of system optimization are discussed illustrating the influence of basic system design possibilities. Design variants investigated include alternatives for anode and cathode gas supply and gas recycling, methods to achieve self-sufficiency on water for the reforming of natural gas, and recovery of unspent fuel from the anode exhaust. Especially in small systems for decentralized applications, e.g., industrial cogeneration, system simplification is decisive to bring down the capital cost of the balance-of-plant. Trade-offs between system complexity and efficiency are possible to optimize the economy. In large plants, high-temperature fuel cell can be supplemented with bottoming cycles for best fuel utilization. Gas turbines and steam turbines can be evaluated, having strong influence on the system design pressures and, therefore, system cost.

Introduction

Fuel cells for stationary power generation applications are being pursued on a large scale worldwide in an effort to achieve commercialization before the turn of the century. Most research and development work is focused on the technology of the cells proper, to improve the performance characteristics of cell stacks.

While it is true that the fuel cell stack is the innovative nucleus of this new power conversion technology, the overall system determines such parameters as fuel efficiency, capital cost, and operating and maintenance cost. These parameters are decisive for the acceptance of fuel cells on the commercial market. The peripheral components around the fuel cell stack – usually named balance-of-plant (BOP) – will typically have twice the capital cost of the cell stack. Under series production conditions, the cost of electricity will be more dependent on intelligent designs of overall systems than on technical improvements of the cells.

Some aspects of system optimization are discussed here illustrating the influence of basic system design possibilities. All of the examples are based on molten carbonate fuel cell (MCFC) stacks, but many issues are readily transferred to other fuel cell types for stationary use, i.e., the phosphoric acid fuel cell (PAFC) and the solid oxide fuel cell (SOFC).

Cost reduction potentials

A fuel cell stack consists essentially of a large number of repeat components. These parts account for approximately 80% of the stack cost. Under commercial conditions,

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high volume production of the repeat components will lead to very substantial cost reductions, limited essentially by the cost of the material included in the stack.

For the BOP subsystems, the situation is different. These subsystems are made up from fairly mature components with wide applications in other fields of plant engineering. No large cost reduction potential can be expected from further development of these components. In addition, production lots of BOP components will stay moderate even assuming a good market penetration of fuel cell power systems. In very large fuel cell power systems, economies of scale will lead to some reduction of the specific cost of BOP subsystems, but these very large power systems are not expected to be commercial before the year 2010.

In summary, series production effects will not substantially reduce the cost of BOP. The only way to bring overall system cost down to commercially acceptable levels will be via system optimization in the early phases of system development work.

System design alternatives

The efficiency of fuel cell power systems can be traded against system complexity. A comparative evaluation of a wide variety of design concepts performed at the author's centre, indicates that simpler systems generally tend to exhibit a better economy. This is especially true for smaller power systems.

In the following some of these design concepts will be discussed, indicating possible ways of system simplification. All diagrams presented here do not consider any gas pretreatment or cleanup subsystems. The waste heat utilization is not shown.

MCFC with H_2 recycling

This concept (Fig. 1) has been devised for a large coal gas fed MCFC power station. It is designed for maximum efficiency and incorporates a unique electrochemical subsystem for the recovery of unused hydrogen in the anode exhaust circuit. After passing heat exchangers and a shift reactor, the anode exhaust is fed into an electrochemical hydrogen separation device (EHSD). This component, developed by Energy Research Corporation, resembles a PAFC operated in an inverse manner. Supplied with some amount of electrical energy, the EHSD efficiently separates the hydrogen from the anode exhaust gas.

While the unspent hydrogen is fed back into the anode supply circuit the exhaust gases are cooled down to condensation temperature supplying enough water for self-sufficiency of the plant.

The cathode loop of the plant is of a conventional type. This design exhibits an excellent fuel utilization, leading to an overall efficiency of 57% for coal gas and approximately 67% for natural gas. However, the complexity of the system will result in an extremely high investment cost. The main cost drivers are not only the additional electrochemical devices for hydrogen recovery, but also the heat exchange and thermal control equipment required by the specific operating temperatures of the individual chemical and electrochemical processes.

MCFC with hot anode gas feedback

This design (Fig. 2) represents the opposite, a simplified design which is shown here for contrast. It is characterized by simplified water recovery from the anode loop. Approximately half of the anode exhaust is fed back to the fuel input, supplying

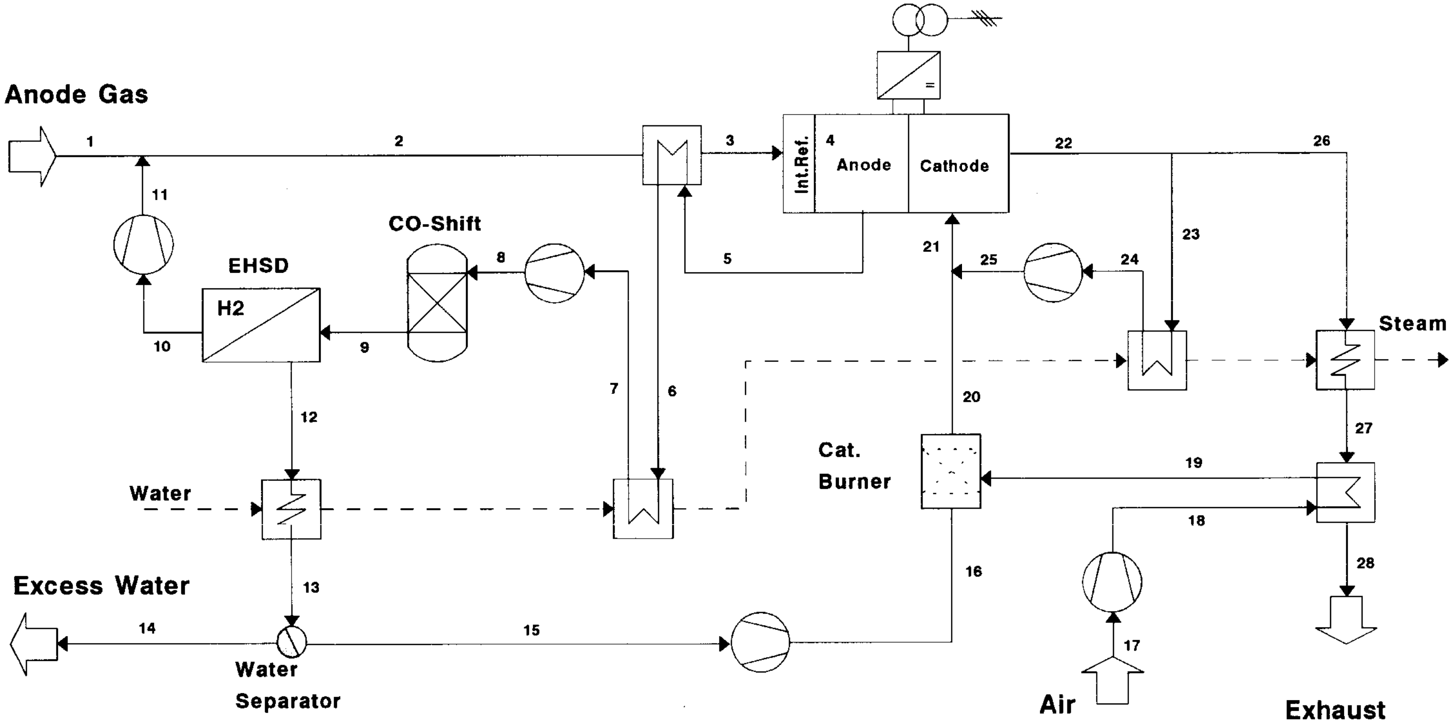

Fig. 1. Molten carbonate fuel cell with H_2 recycle; coal gas, efficiency: 57%.

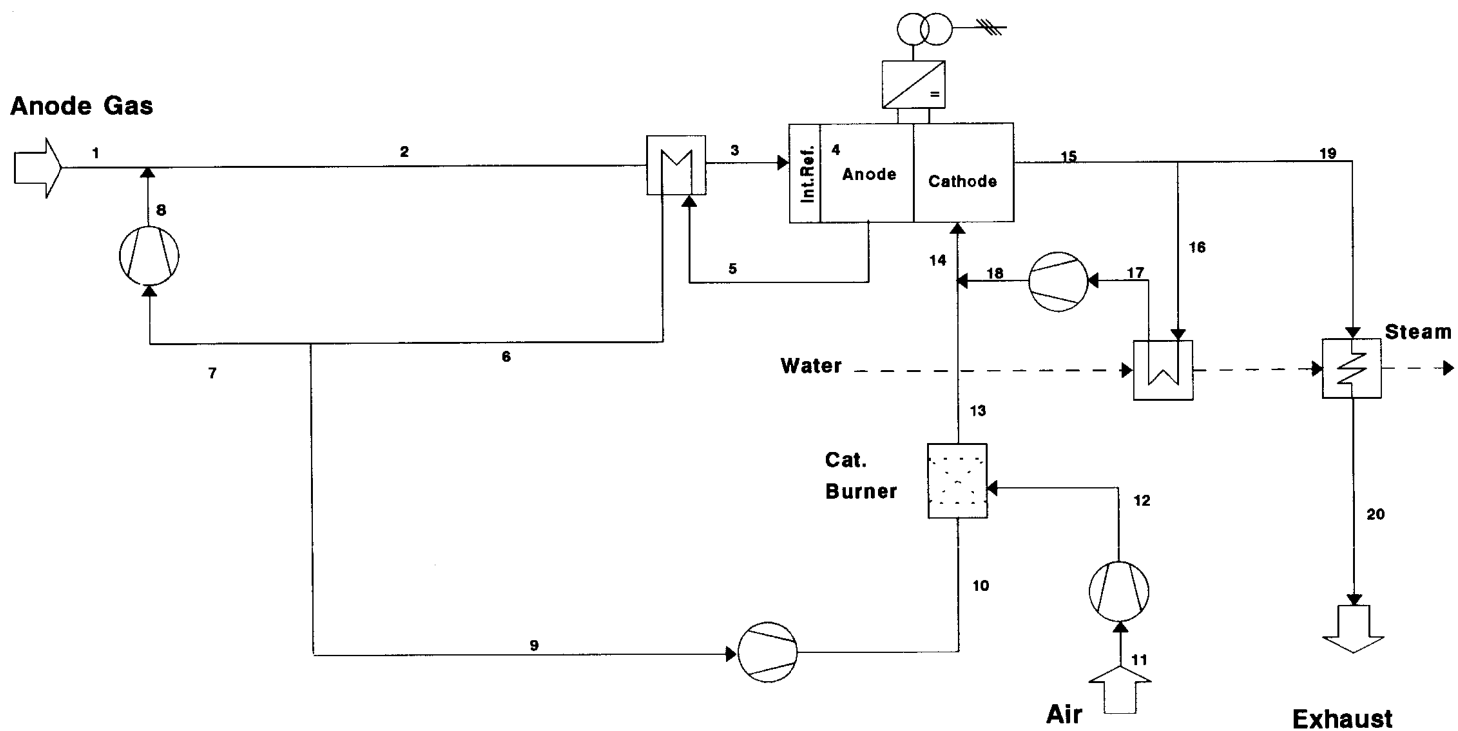

Fig. 2. Molten carbonate fuel cell with anode gas recycle; coal gas, no water separation, efficiency: 49%.

sufficient water for the reforming of the methane content of the fuel gas. The other half of the anode exhaust is simply burnt in a catalytic burner and dumped into the cathode circuit. The reduction of the system complexity is obvious. The investment cost is greatly reduced by eliminating the hydrogen recovery loop, and also by the deletion of the equipment for water condensation and reheating.

The penalty to be paid for this extreme system simplification lies in a reduced efficiency. Although some of the unspent hydrogen is fed back with the anode exhaust gases to the fuel input, the carbon dioxide contents in the anode loop reduce the Nernst potential, and therefore the cell voltage to values below 700 mV.

The low efficiency and the questionable corrosion stability of certain design components in this concept lead to the conclusion that system simplification has been taken too far. Therefore, two intermediate simplification steps for natural gas MCFC systems are illustrated.

MCFC natural gas systems with reduced complexity

A basic natural gas MCFC system (Fig. 3) has a single pass anode circuit with water separation and a catalytic afterburner. The cathode air is recycled for cooling while the exhaust heat is used to preheat the fresh air and to re-evaporate the water for reforming. The design is classical, but it may be further simplified. First, we may delete the fresh air preheater. Fresh air is simply mixed with hot air from the cathode recycle loop (Fig. 4).

In a second step, we may eliminate the anode exhaust feedback loop completely (Fig. 5). The anode exhaust is fed directly to the catalytic burner, and mixed into cathode gas feedback loop. The water to supply the reforming steam is separated by cooling down the cathode exhaust below condensation temperature.

The main advantage of this approach is the direct pneumatic coupling of the anode and cathode gas streams, greatly reducing differential pressure problems in the fuel cell.

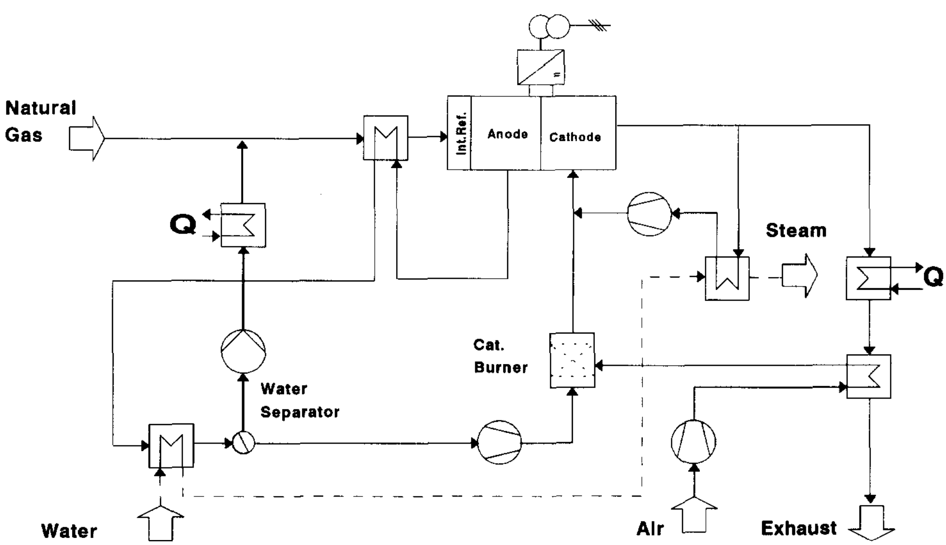

Fig. 3. Molten carbonate fuel cell, basic system; natural gas.

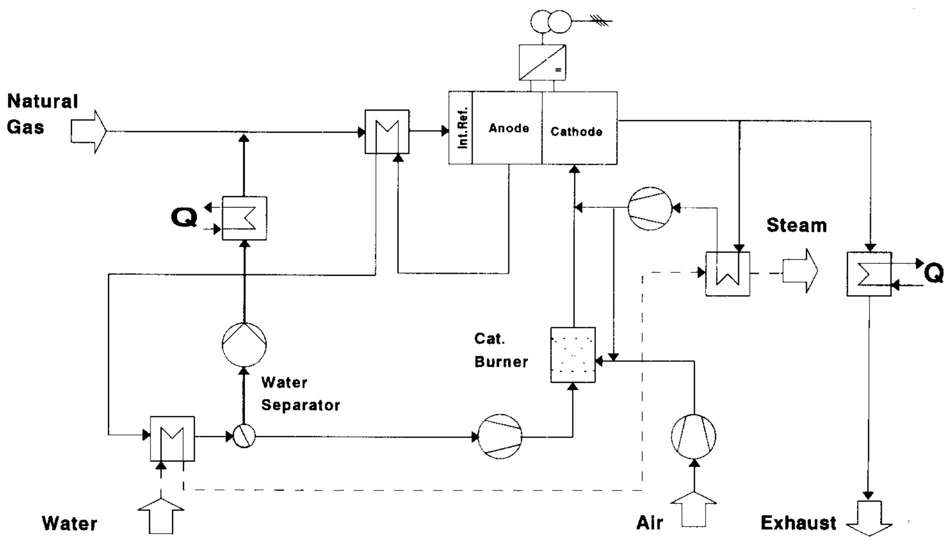

Fig. 4. Molten carbonate fuel cell, simplified air supply; natural gas.

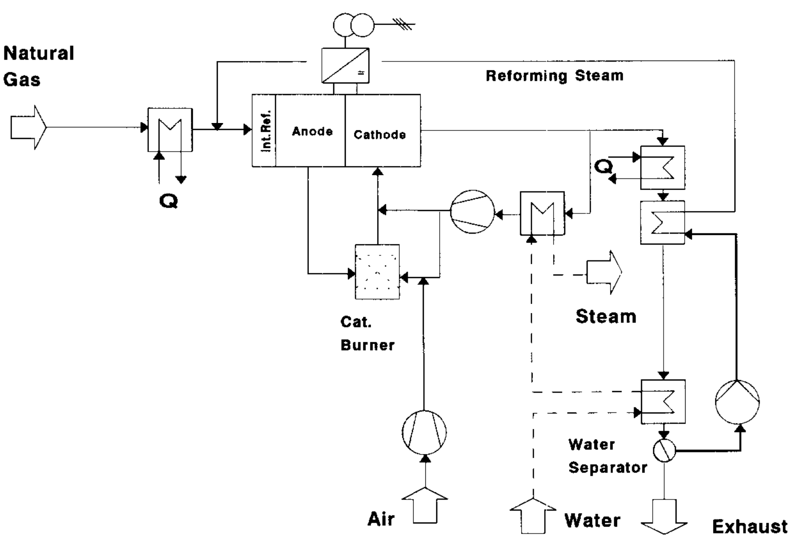

Fig. 5. Molten carbonate fuel cell, simplified anode circuit; natural gas.

Checklist for fuel cell system designers

When a fuel cell system is designed the following characteristics of a good design concept may be checked:

(i) A minimum number of: material flows; operating states; fixed temperatures; temperatures; components; interfaces, and control.

(ii) Physical solution to problems; example: anode and cathode in a pneumatic short circuit, instead of differential pressure control.

(iii) Mechanical and thermal integration.
(iv) Pneumatic integration (low flow resistance in the cathode circuit).
(v) Minimized consumable and parasitic power.
(vi) Modularity.
(vii) Main system components identical for all system variants ('family concept').
(viii) Additional merits: high efficiency; low cost; safety; reliability; maintainability, and interchangeability.

Bottoming cycle subsystems and fuel cell pressure

In large-scale power plants the heat produced by high-temperature fuel cells will be used in a bottoming cycle for additional electricity production, pushing the overall system efficiency to well above 66%. Gas turbines or steam turbines can be selected as bottoming systems, and combinations of both have been proposed.

In the literature, the comparative evaluation of the alternatives is usually based on efficiency and cost data. Additional parameters such as a potential for technological growth are also taken into account. In most cases, gas turbines are preferred to steam turbines because of their lower investment cost and the excellent efficiency of recent advanced designs.

The choice between a gas turbine or a steam turbine is decisive in influencing the operating pressure of the fuel cell system. For a steam turbine, the steam pressure and the fuel cell operating pressure can be chosen independently, because the fuel cell system is decoupled from the turbine by the waste heat boiler. However, the fuel cell serves as a replacement for the gas turbine combustion chamber, requiring the fuel cell to operate at high pressures (typically 30 bars).

High operating pressures tend to increase specific corrosion problems in the fuel cell. In MCFC, cathode dissolution increases sharply with operating pressure. But even if we assume all pressure-related problems in the fuel cells to be solved, another pressure-related problem seems to have been overlooked.

High-temperature fuel cells are characterized by a moderate energy density, in the order of 0.1 MW/m^3. If we suppose that a fuel cell stack has 300 cells of 1 m^2 area and a power output of 250 kW, this stack will minimally require a cylindrical pressure vessel of 1.5 m diameter $\times$ 3 m height. At 30 bars and wall temperatures below 500 °C a wall thickness of $\sim$18 mm is required, corresponding to a mass of 2.5 tons of high performance steel. As a rule of thumb, 10 tons of steel are needed per MW of fuel cell output power for the pressure vessels alone, not considering those for other BOP components.

It is quite obvious that the cost of system pressurization to 30 bars is prohibitive. The trade-off between gas and steam turbines must be reconsidered, taking these factors into account.

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