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Modeling and optimization of a 1 kW_e HT-PEMFC-based micro-CHP residential system

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ABSTRACT

A high temperature-proton exchange membrane (HT-PEMFC)-based micro-combined-heat-and-power (CHP) residential system is designed and optimized, using a genetic algorithm (GA) optimization strategy. The proposed system consists of a fuel cell stack, steam methane reformer (SMR) reactor, water gas shift (WGS) reactor, heat exchangers, and other balance-of-plant (BOP) components. The objective function of the single-objective optimization strategy is the net electrical efficiency of the micro-CHP system. The implemented optimization procedure attempts to maximize the objective function by variation of nine decision variables. The value of the objective function for the optimum design configuration is significantly higher than the initial one, with a 20.7% increase.

1. Introduction

A residential application of combined-heat-and-power (CHP) technology is a micro-CHP system, providing electricity and heat (hot water and space heating) for a detached single-family household. Such a system is designed to convert the chemical energy in a fuel into both electrical power and useful heat [1–5]. Micro-CHP systems operating on natural gas must be coupled with a fuel processing unit, to allow conversion of natural gas to hydrogen. Balance-of-plant (BOP) components are also needed to perform various necessary tasks, such as air compressing or water pumping, while heat exchangers are necessary for the thermal management of the system. The thermal management of the system includes heating/cooling of components (e.g. steam reforming), and also heat recovery to satisfy the residential load profile (e.g. space heating). A thermal storage tank is coupled with the system to provide greater operational flexibility during transient load demands.

Micro-CHP systems can be categorized into combustion- and fuel cell-based. Although combustion-based technologies are more mature and currently available in the market, fuel cell-based systems are considered more promising for a number of reasons. Combustion-based systems, such as the internal combustion engine technology, are not suitable for micro-CHP applications mainly due to their high thermal-to-electric ratio (TER) [1], and also due to their low efficiencies at part-load operation. Fuel cell-based stationary power generation technology is capable of achieving high efficiencies, with lower emissions as compared to combustion-based systems. Also these systems have simple routine maintenance requirements and quiet operation [1,6,7].

The operating temperature in a fuel cell stack is an important element for the efficiency and the degradation of

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the membrane. Fuel cell technologies operating at high temperatures can lessen the cooling requirements, simplify water management and reduce contamination problems. High temperature-proton exchange membrane fuel cells (HT-PEMFC) utilize a Polybenzimidazole (PBI) membrane, which operates at temperatures between 150 and 200 °C. It is therefore an ideal match for a micro-CHP system, because not only the rates of electrochemical kinetics are enhanced and water management and cooling is simplified, but also useful waste heat can be recovered, and lower quality reformed hydrogen may be used as fuel [8–11].

A global optimization strategy is usually desirable for multi-component systems, such as the micro-CHP system under study, because the global maximum is not just the best solution to the optimization problem, but also because local maxima can severely confound the interpretation of the results of studies investigating the effects of model parameters [12]. A stochastic method, such as genetic algorithms (GA), can solve a problem with a systematic multi-start approach with random sampling.

2. System layout

The proposed system, shown in Fig. 1, is modeled in the commercially available software EES (Engineering Equation Solver). Natural gas, used as the system fuel input, is converted to a hydrogen-rich mixture, throughout a fuel processing series of steps. The fuel processing subsystem includes a desulfurizer, steam methane reforming (SMR) reactor, water gas shift (WGS) reactor and combustor. The fuel cell stack receives the reformate fuel, without any water content since this is removed by the condenser/water-knock out stage. The fuel cell stack exhaust mixture is then fed to the combustor, since it contains a large amount of air mixture, which can be used in the combustion process. The exhaust mixture also contains small traces of unreacted methane and carbon monoxide, which are combusted in the combustor. If additional air and/or natural gas are needed, they are provided by the air blower and the fuel line, respectively. The combustor output flue gas is used in the SMR reactor, the fuel preheater, the steam generator, and finally in the thermal storage tank for cogeneration purposes. The thermal management of the system is provided by the use of four heat exchangers.

The model includes 28 state points (nodes). In order to synthesize and design the proposed system, the energy requirements for a representative residential building must be established. For the current research study, the representative residential building is a typical Danish single-family household (130 m^2 house with four persons). A micro-CHP unit of approximately 1 kW_e is considered. The type of residential loads considered, include the electrical load, the space heating load and the hot water load. The mean residential load requirements are based on [4,13] and are shown in Table 1. The current research study assumes the electrical load and the combined heating load as dependent variables, calculated with respect to the values of the independent parameters

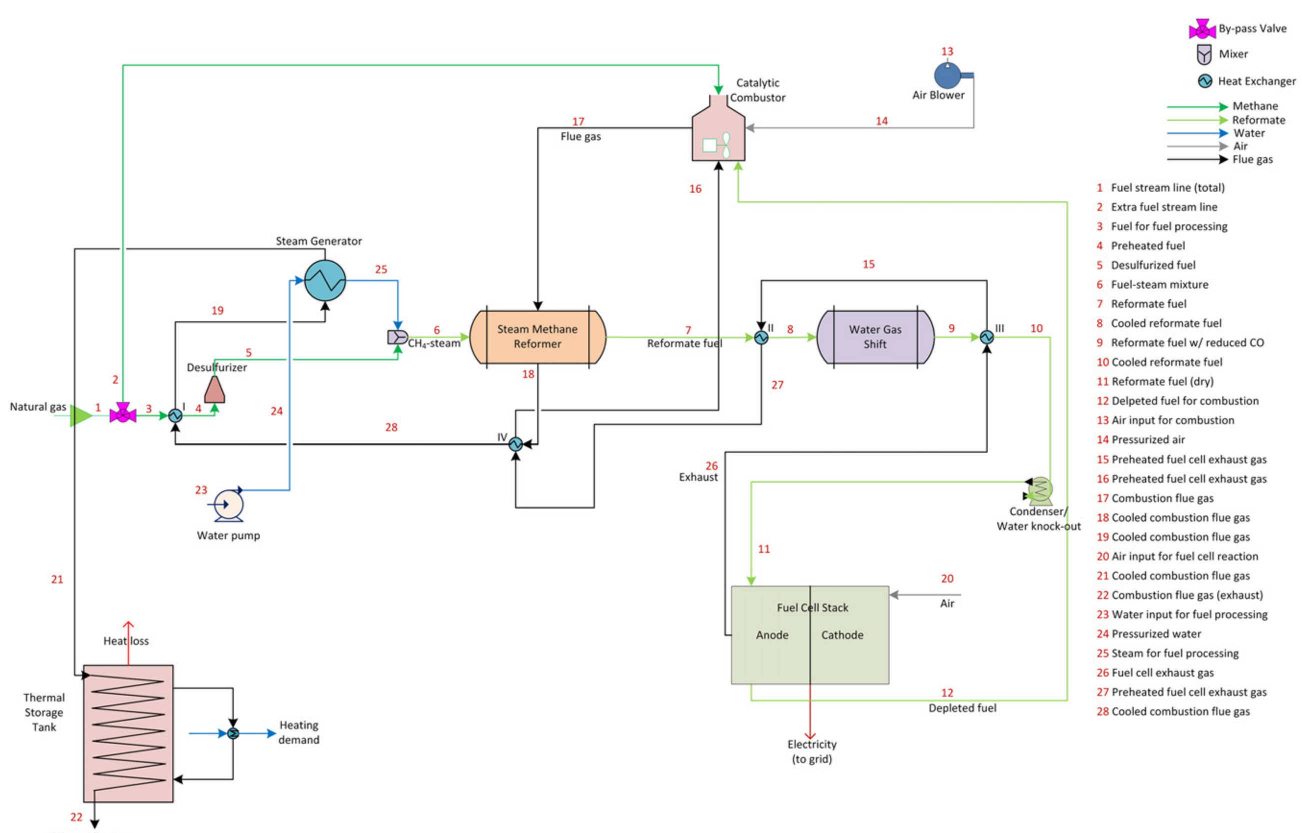

Fig. 1 – Configuration of the proposed micro-CHP system.