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# Steam-to-carbon ratio control strategy for start-up and operation of a fuel processor

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## ABSTRACT

The purpose of this work is to suggest a steam-to-carbon ratio (SCR) control strategy for the start-up and operation of a fuel processor and to experimentally verify this strategy. To overcome ambient temperature variability and manufacturing deviations, a controlled SCR method (CSM) is suggested. The CSM controls the water flow rate independently through heat exchangers (HEXs) to maintain a constant inlet temperature of the reactors. To consistently satisfy the target SCR value, the remaining water after control is fed to the last HEX used as a buffer. To verify the CSM, seven gasoline fuel processors (GFPs) were constructed. The GFPs consisted of an autothermal reformer (ATR), hydrodesulphurization (HDS), a high-temperature shift reactor (HTS), a medium-temperature shift reactor (MTS), a preferential oxidation reactor (PROX), a HEX, and an exhaust gas burner. Water was individually supplied to HEX #1 ~ HEX #4 as a cool-side fluid. One of the GFPs was operated at a low ( $-32\text{ }^{\circ}\text{C}$ ) and a high ( $50\text{ }^{\circ}\text{C}$ ) temperature. The CSM maintained a constant inlet temperature of the reactors; only the inlet temperature of the PROX was affected by the ambient temperature thanks to the CSM. Temperature results for the other six GFPs showed that manufacturing deviations appeared only in the inlet temperature of the PROX by the CSM. To confirm the effect of the CSM on durability, 38 start–stop cycles were performed over 314 h of operation. The results showed that the repeated use of the CSM led to a slow degradation of efficiency, while the temperatures of the reformer and reactor remained steady during cycling testing.

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## Introduction

Fuel processors have been developed for use in fuel cell systems and have been investigated as alternative energy technologies. Although hydrogen is considered an ideal fuel for fuel cell systems due to their high efficiencies and simple system designs, until recently the direct use of hydrogen in fuel cell systems has been stymied by the lack of a hydrogen infrastructure. Furthermore, hydrogen has a relatively low energy density compared with hydrocarbon fuels such as natural gas. While liquid hydrogen has a high energy density,

it must be stored at extremely low-temperatures and high-pressures; this makes its storage and transportation difficult.

A fuel processor that produces hydrogen from hydrocarbon fuels is advantageous because it enables a high energy density and easy fuel handling. Therefore, automobile companies have studied fuel-processing technology as a complement to standard hydrogen storage in a compressed hydrogen tank. A fuel cell-powered vehicle equipped with a fuel processor can receive fuel from existing gas stations. Additionally, fuel processors have been used to supply hydrogen to stationary fuel cell systems such as power plants and in residential-scale power generation [1]. Submarine manufacturers, in particular

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Howaldtswerke–Deutsche Werft (HDW) in Germany, have been developing methanol fuel processors to increase the amount of time submarines can spend underwater [2]. Recently, the demand for auxiliary power units (APUs) using fuel cells has grown along with the development of information technology. Fuel cell-based APUs are mainly studied for military [3–6] and leisure applications [7–10].

Many researchers have proposed layout and control strategies for the effective supply of hydrogen-rich reformat gas in fuel processors. Springmann et al. [11] performed simulations based on 1-D multiphase dynamic models for autothermal reformers (ATR) to investigate the optimal initiation strategy at 20 °C. Sommer et al. [12] introduced a thermally integrated fuel cell system. The main features of the fuel processor included an ATR, heat exchanger (HEX) #1, a high-temperature shift reactor (HTS), HEX #2, a low-temperature shift reactor (LTS), and a preferential oxidation reactor (PROX). The water was supplied to HEX #2 and then evaporated by HEX #5 behind the external burner. Steam was then mixed with air, and the mixture was preheated by HEX #1 using the heat of the reformat gas leaving the ATR. Hu et al. [13] studied controller design and analysis for the autothermal reformation of gasoline using a fuel processor composed of a single ATR and HEX. Lee et al. [14] introduced a fuel processor that incorporated methane reforming, sulfur removal, and water gas shift (WGS) processes into a compact 22.8 cm (dia.) × 42.4 cm (high) reactor vessel. The ATR bed temperature was controlled via the oxygen-to-carbon ratio (OCR) and steam-to-carbon ratio (SCR) in the feed, and the ZnO and WGS bed temperatures were controlled by placing two HEXs in the catalyst zones. The process water for the ATR was used as the cooling medium. Qi et al. [15] developed an ATR fuel processor for polymer electrolyte membrane (PEM) fuel cells based on gasoline. The main features of the fuel processor included an ATR, HEX #2, an HTS, HEX #3, an LTS, HEX #1, and a PROX. The water was divided into three streams after preliminary heating by HEX #1. The first stream (W1) was sprayed into the mixer just ahead of the ATR reformer after passing through the ATR's catalyst bed; the second stream (W2) was supplied to HEX #2 before merging into the ATR zone to participate in the reforming reaction; and the remaining water (W3) was supplied to HEX #3 to control the inlet temperature of the LTS. However, the ATR outlet and WGS inlet temperatures varied with the  $W_2/C$  molar ratio. The overabundant water from W2 did not fully evaporate and mix with the other reactants, which eventually interfered with the ATR reaction due to the limited inlet (premixing) temperature. Goebel et al. [16] suggested a rapid fuel processor start-up method for automotive fuel cell systems. A fuel processor was constructed incorporating two burners with direct steam generation by water injection into the burner exhaust. These burners with direct water vaporization enabled rapid fuel processor start-up. Northrop et al. [17] proposed the use of heat provided to an external pre-boiler to control the axial temperature gradient in a series of fuel processor reactors. A counter-flow heat exchanger was embedded in the fuel processor using the water's vaporization heat to maintain a near-isothermal temperature profile in the PROX section. However, the inlet temperature was changed by the rated thermal input. Jaggi et al. [18] studied an integrated configuration incorporating a

fuel cell and an autothermal ethanol reformer for a 5 kW stand-alone power unit. The integrated high-temperature polymer electrolyte membrane fuel cell (HT-PEMFC) consisted of a mixer, a fuel pre-heater, a reformer, a fuel cell stack, and a combustor. The water was mixed with ethanol, and the mixture was fed to the pre-heater unit heated by the combustor. Subsequently, the hot stream of vaporized ethanol and water was fed to the heat exchanger installed at the ATR outlet. Lee et al. [19] developed a compact and highly efficient natural gas fuel processor for 1-kW residential PEM fuel cells. The fuel processor consisted of a steam reformer, a WGS, a heat exchanger, and a burner. The water was partially evaporated at HEX #1 by heat-exchanging with the burner exhaust gas and completely evaporated at HEX #2 by heat-exchanging with the reformat gas from the reformer. The water was then mixed with the  $CH_4$  feed at the required SCR and introduced into the reformer. However, the inlet temperature of the WGS was not controlled by the SCR. A gasoline fuel processor (GFP) for vehicle applications was introduced by Severin et al. [20] Its main features included an ATR, HEX #1, an HTS, HEX #2, an LTS, and a PROX. Water was fed to HEX #1 and mixed with air that passed from the HEX #2 to the HEX #3 of the external burner. The mixture of steam and preheated air was supplied to the ATR. The concept of water injection into HEX #1 allowed control of the inlet temperatures so that the HTS and LTS could be operated at their optimal point. Maximini et al. [21] introduced a start-up strategy for the diesel fuel processor of PEM fuel cells. The fuel processor module included mixture preparation, a 10 kW microchannel steam reformer, two WGSs, and evaporators for steam generation. The new approach included the reactive heating of WGS reactors using reformat gas from oxidative steam reforming instead of the sequential heating of the fuel processor. The water was separately supplied to three HEXs installed at each stage. However, the exact method for controlling the water was not explained.

Unlike a stationary fuel cell system, APUs are used in various environments. Therefore, the fuel processor in an APU must be capable of starting and operating in a wide range of temperatures. To do so, the temperature of the reactors must be kept constant under various conditions to maintain performance. However, previous studies have not sufficiently considered control methods. In addition, the usefulness of control strategies has not been verified by testing multiple prototypes. This study introduces a system layout and SCR-based control strategy required to maintain the temperature of the reformer and reactor in the presence of ambient temperature variability and manufacturing deviations. An experimental design for the fuel processor was developed, and the fuel processor was operated at a low- and a high-temperature per the proposed control strategy. In addition, the usefulness of the control strategy was verified by experiments with six more GFPs, and daily start and stop (DSS) tests confirmed the results.

## Methods

### Fuel processor layout

A fuel processor is designed to supply hydrogen-rich reformat gas to a HT-PEMFC stack for APU applications.

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