

Short communication

# Design and development of a diesel and JP-8 logistic fuel processor

Subir Roychoudhury<sup>a,\*</sup>, Maxim Lyubovsky<sup>a,1</sup>, D. Walsh<sup>a,2</sup>,  
Deryn Chu<sup>b,3</sup>, Erik Kallio<sup>c,4</sup>

<sup>a</sup> Precision Combustion Inc., 410 Sackett Point Road, North Haven, CT 06473, United States

<sup>b</sup> Army Research Laboratory, Amsrl-SE-DC, 2800 Powder Mill Road, Adelphi, MD 20783-1197, United States

<sup>c</sup> US Army TARDEC, 6501 East Eleven Mile Road, AMSRD-TAR-N/272, Warren, MI 48397-5000, United States

Received 20 December 2005; accepted 31 December 2005

## Abstract

The paper describes the design and performance of a breadboard prototype for a 5 kW fuel-processor for powering a solid oxide fuel cell (SOFC) stack. The system was based on a small, modular catalytic Microlith auto-thermal (ATR) reactor with the versatility of operating on diesel, Jet-A or JP-8 fuels. The reforming reactor utilized Microlith substrates and catalyst technology (patented and trademarked). These reactors have demonstrated the capability of efficiently reforming liquid and gaseous hydrocarbon fuels at exceptionally high power densities. The performance characteristics of the auto-thermal reactor (ATR) have been presented along with durability data. The fuel processor integrates fuel preparation, steam generation, sulfur removal, pumps, blowers and controls. The system design was developed via ASPEN<sup>®</sup> Engineering Suite process simulation software and was analyzed with reference to system balance requirements. Since the fuel processor has not been integrated with a fuel cell, aspects of thermal integration with the stack have not been specifically addressed.

© 2006 Elsevier B.V. All rights reserved.

**Keywords:** JP-8; Diesel; ATR; Desulfurization; Microlith(R); Reformer

## 1. Introduction

The Microlith catalyst consists of mesh-like substrate coated with high surface area ceramic and active metal catalyst. This provides extremely high mass and heat transfer properties as well as high surface area which are important for fast oxidation reactions [1]. Microlith based reforming systems have demonstrated operation at low O/C and S/C ratios [1–4]. This paper describes the fuel processor under six sections: (i) fuel processor system model; (ii) ATR design; (iii) ATR performance data; (iv) ATR durability; (v) fuel processor control, balance of plant (BOP) and integration issues; (vi) desulfurizer performance.

## 2. Fuel processor system design

ASPEN<sup>®</sup> modeling was used to optimize the system layout with respect to water addition/recycle/recapture and their associated impacts. The system configuration is shown in Fig. 1. The system operated at approximately 1–2 atm. The ATR feed water was delivered to a heat exchanger where it was vaporized prior to mixing with air supplied at the same pressure. The steam/air mix was combined with hydrocarbon fuel (represented by dodecane) through a nozzle, prior to delivery to the ATR. The ATR was represented as an adiabatic reactor yielding an equilibrium product distribution. The hot ATR product served as the heat source for vaporizing the feed water.

Typically, the feed O/C ratio was fixed and two convergence criteria were imposed on the simulation. The first required that the temperature of the steam exiting the heat exchanger be sufficient to achieve a specified ATR mixed feed temperature (300–400 °C). The second required that the temperature of the cooled ATR product leaving the heat exchanger be compatible with effective sulfur removal in a downstream ZnO bed (typically 300–350 °C). This was controlled by regulating the water feed rate. Thus, for a given O/C, the S/C ratio was that value

\* Corresponding author. Tel.: +1 203 287 3700; fax: +1 203 287 3710.

E-mail address: [sroychoudhury@precision-combustion.com](mailto:sroychoudhury@precision-combustion.com)

(S. Roychoudhury).

<sup>1</sup> Present address: H<sub>2</sub>Gen Innovations, Inc., 4740 Eisenhower Ave., Alexandria, VA 22304, United States. Tel.: +1 203 287 3700; fax: +1 203 287 3710.

<sup>2</sup> Tel.: +1 203 287 3700; fax: +1 203 287 3710.

<sup>3</sup> Tel.: +1 301 394 0308; fax: +1 301 394 0273.

<sup>4</sup> Tel.: +1 586 770 5351.

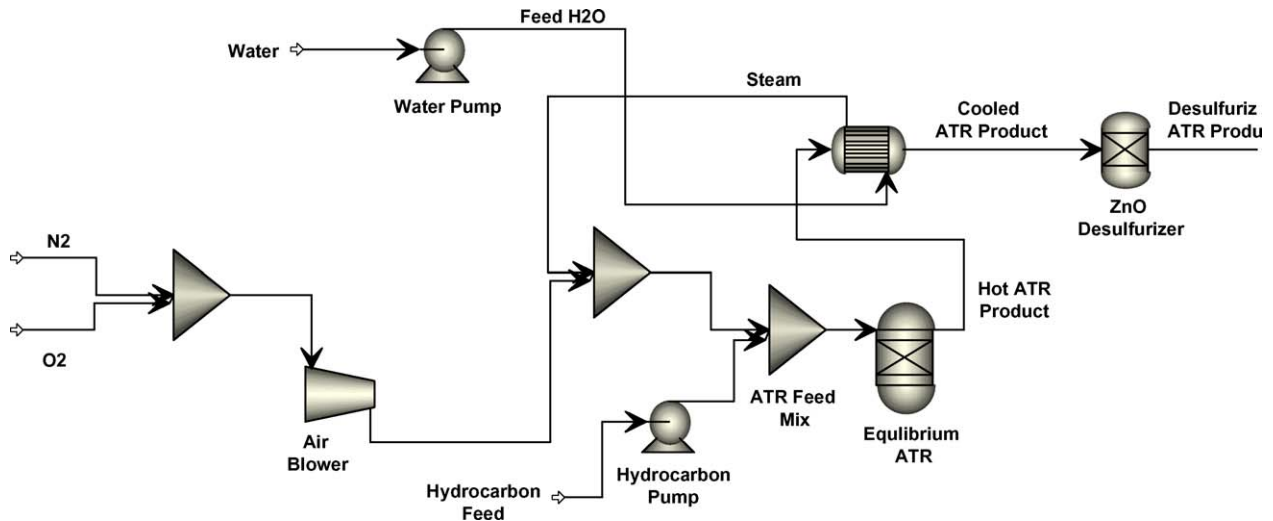


Fig. 1. ASPEN® representation of the system schematic.

which simultaneously satisfied these two requirements. Case studies showed that there was a preferred O/C range ( $\sim 1.1$ – $1.2$ ) below which target ATR feed temperatures could not be achieved and above which system efficiencies declined excessively. As an example, at a fixed O/C of 1.2, acceptable operation for a  $400^\circ\text{C}$  target ATR feed temperature and a  $300^\circ\text{C}$  ATR product temperature exiting the heat exchanger, could be obtained at a feed S/C of 2.16, resulting in 75% thermal efficiency for the reforming system (including BOP losses but not including the fuel cell efficiency). The model included a minimal degree of thermal integration, because it did not incorporate a fuel cell. Thermal and fluid integration with the downstream SOFC will be required when this fuel processor as part of a complete power source.

### 3. ATR design

The ATR reactor is the core of the fuel processing system. It incorporates a catalyst bed, a fuel/air/steam injector/atomizer/mixer and a glow plug. The test ATR reactor was

enclosed in a quartz housing to enable visual observation of the catalyst performance. The reactor was also instrumented with multiple thermocouples and gas analysis probes for studying temperature and flow distribution within the catalyst bed. The 5 kW ATR and a picture of it during testing are shown in Fig. 2. The assembly was 3.3 in. tall and 2 in. in diameter.

### 4. ATR performance data

During start up, a glow plug was used to pre-heat the catalyst to the lightoff temperature. After the catalyst temperature reached the lightoff point, fuel and air flows (at ambient temperature) were started. This initiated the oxidation reaction and released additional heat. The glow plug was shut off at this point and the ATR transitioned to steady operational condition in about 1 min. As the catalyst lit off, the heat of reaction was used to vaporize water. Consequently steam flow to the reactor was started. This caused the temperature to decrease on the front of the catalyst bed, such that more air could be added to the

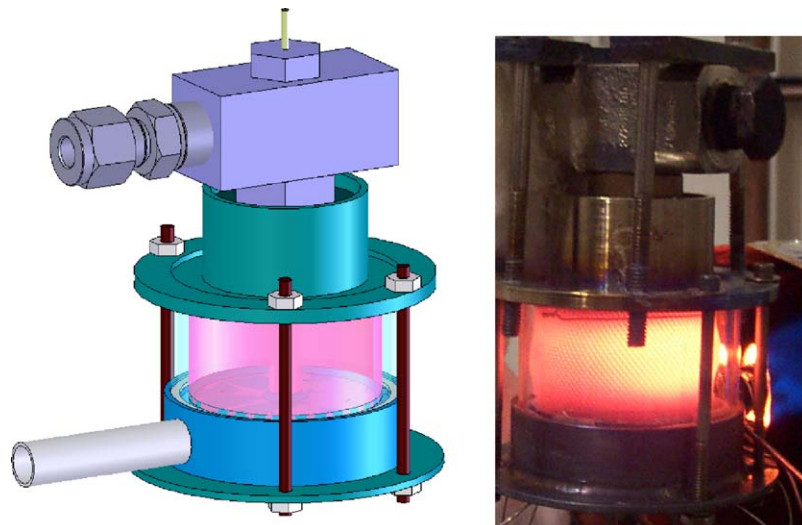


Fig. 2. A solid rendering of the ATR and a photograph of the operating reactor.

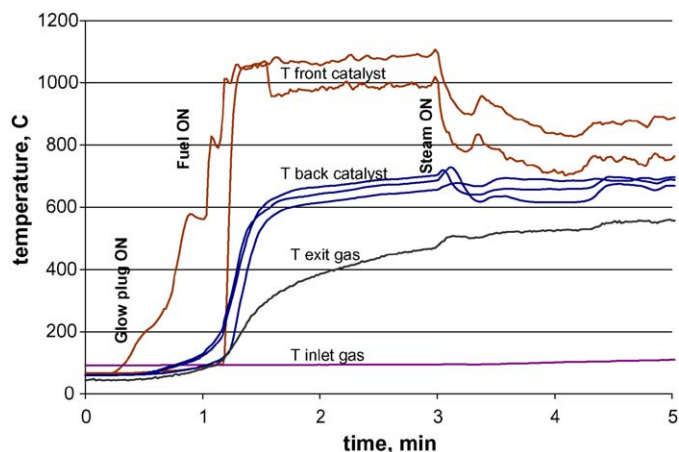


Fig. 3. Start up of the ATR reactor.

reactor and complete fuel conversion achieved. Reactor temperatures during the lightoff process are shown in Fig. 3. Lightoff at ambient conditions as well as at  $-40^{\circ}\text{C}$  was demonstrated.

The reformate gas composition was analyzed by a GC to determine fuel conversion and reforming efficiency. ATR performance dependence on inlet temperature, air-to-fuel ratio (O:C) and steam-to-fuel ratio (S:C) was investigated (Fig. 4). It was found that the reactor could be operated with low steam addition (S:C  $\sim 1$ ). It was also found that increasing the inlet temperature improved reactor performance. At  $400^{\circ}\text{C}$  and S:C = 1.1, the JP-8 reforming efficiency (LHV based) was 65%. The reactor exhibited similar performance when operated on diesel fuel. Note that due to equipment tolerances analytical considerations resulted in a maximum 95% material balance. The flattening of the conversion curve indicates that this corresponds in actuality to essentially complete fuel conversion.

## 5. ATR durability

Four ATR catalyst formulations were evaluated prior to performing a durability test. Screening was performed for 50 h with a feed stream of Jet-A *spec* fuel containing 1500 ppm sulfur. Fuel feed rate in these tests was set at  $6\text{ ml min}^{-1}$ , which corre-

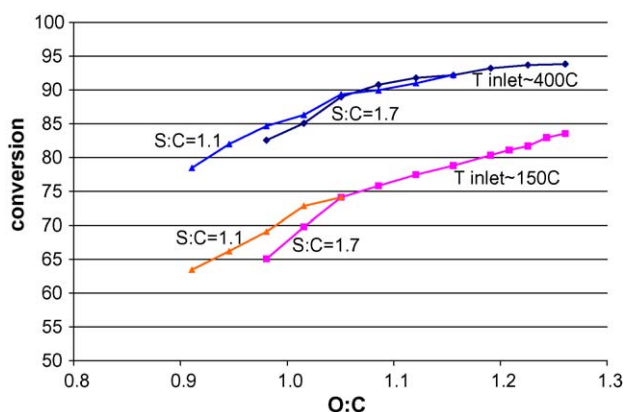


Fig. 4. Dependence of fuel conversion on O:C, S:C and inlet temperature (reformate GC analysis).

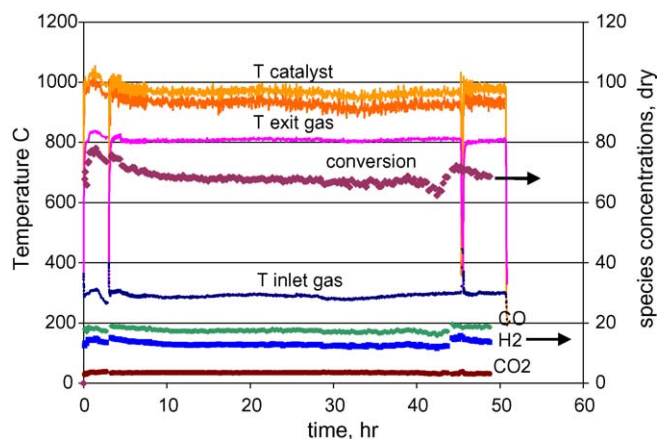
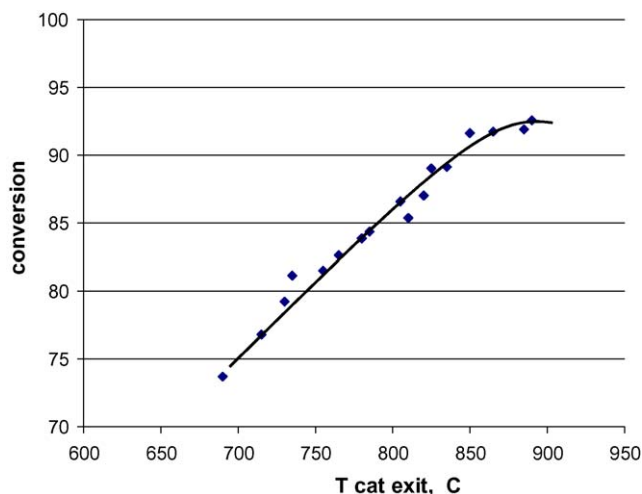


Fig. 5. ATR performance w. 1500 ppm fuel-sulfur at O:C=0.96; S:C=1.44.

sponds to 3.5 kW of thermal power input, and the air and water feeds were set to O:C  $\sim 1.0$  and S:C  $\sim 1.5$ . Temperatures, fuel conversion and hydrogen concentration in the reformate stream for one of the catalysts tested are shown in Fig. 5. The results show steady performance of the catalyst over 50 h after an initial decrease in conversion. Note that the fuel conversion as well as CO and H<sub>2</sub> concentrations increased slightly after the reactor was stopped and exposed to air at  $\sim 45$  h. This suggests that the initial deactivation could be due to blockage of active sites by strongly adsorbed species, which could be oxidized and removed by air. The variations in the fuel conversion and H<sub>2</sub> and CO concentrations were due to controller drifts in the O:C and S:C ratios in the reactor feed.

The best performing catalyst was then subjected to a 1000 h test, also with 1500 ppm sulfur Jet-A and operated under similar conditions. After initial problems (over the first 200 h) associated with test equipment were addressed, the performance remained steady during the remaining 800 h. Details of this work will be reported separately.

Fig. 6. ATR fuel conversion dependence on reactor exit temperature S:C=1.05, T inlet =  $400^{\circ}\text{C}$ .

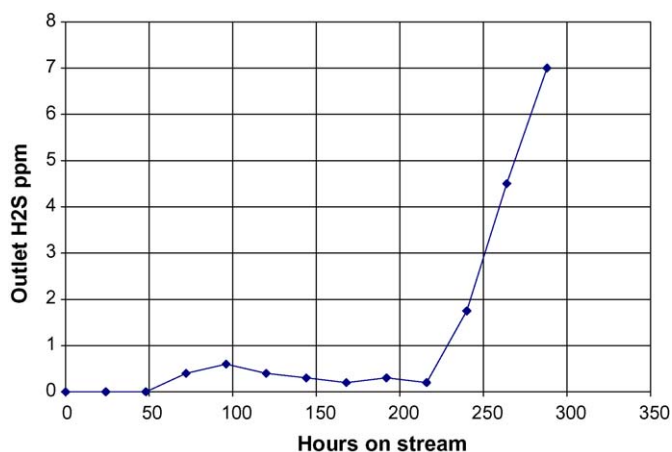


Fig. 7. Sulfur adsorption capacity under simulated conditions.

## 6. Fuel processor control, BOP and integration

The plot of experimentally observed fuel conversion as a function of catalyst exit temperature (Fig. 6) in the ATR suggested nearly linear dependence. The reformate exit temperature, therefore, was a good indicator of the reactor performance and the product quality. At a fixed S:C ratio the ATR performance was controlled by varying the airflow rate based on the ATR exit gas temperature. The fuel, air and water pumps were controlled by varying the control signal to a power conditioning circuit. Algorithms required for start up, transitioning to steady state operation, and shutdown, as well as the ability to detect reactor malfunction and make appropriate control adjustments were incorporated. At start up the reforming reactor operated in dry catalytic partial oxidation (CPOX) mode. Once steam was available the reforming reactor transitioned to ATR mode. Low S:C ratios imply low water needs, which can be recovered from a SOFC exhaust by a small condensing heat exchanger. Integration with a SOFC system will also have to take into account the stack heat-up rate, which is significantly slower than the fuel processor. A National Instruments based system using Labview<sup>®</sup> software was used for control and data acquisition. The volume and weight of the fuel processor were 0.3 ft<sup>3</sup> and 5 kg, respectively, resulting in a power density of  $\sim 1 \text{ kg kW}^{-1}$ .

## 7. Desulfurizer

Thermodynamic equilibrium of ZnO–H<sub>2</sub>S system suggests that at the steam concentration in the reformate stream (20%) and at 350 °C, the sulfur concentration in the reformate stream could

be lowered to <1 ppm. Kinetics of sulfur absorption in the ZnO bed was first tested with synthetic mixtures of 115 ppm H<sub>2</sub>S in methane and nitrogen (dry and with 20% steam addition). Space velocity was varied and sulfur uptake was measured to estimate the kinetic sorption rate and the required ZnO bed size. (Note that due to dilution upon mixing with the other feed components and molar expansion upon reaction in the ATR 115 ppmv of H<sub>2</sub>S in the reformate stream corresponds to  $\sim 1150 \text{ ppm}_w$  of sulfur in the fuel.) Test data suggested that under the actual processor operating conditions the H<sub>2</sub>S concentration could be decreased to below 1 ppm. The ZnO adsorption capacity was tested by flowing the same mixture containing 20% steam and 115 ppm H<sub>2</sub>S at 350 °C through a ZnO bed for an extended period of time. The results showed that at reformate flow rates corresponding to  $\text{GHSV} = 4500 \text{ h}^{-1}$ , the system could operate for more than 200 h before sulfur breakthrough occurred (Fig. 7). The desulfurizer bed was also tested with JP-8 and diesel reformate exiting the ATR and indicated similar trends.

## 8. Conclusions

A 5 kW breadboard Microlith reformer and desulfurizer prototype was designed, developed and successfully tested for operation on JP-8, diesel and Jet-A. Sulfur tolerance and coke resistance of the catalyst was examined over 1000 h. A ZnO-based desulfurizer was used to reduce sulfur concentrations to <1 ppm in the reformate. SOFC quality reformate was generated from a compact and lightweight package. The size of the 5-kW ATR reactor was  $<5 \text{ in.}^3$ , and it was fully operational in 1 min. The fuel processor design used a sulfur trap to reduce sulfur concentrations in the reformate to <1 ppm. A fuel–air–steam mixing and injection system was also developed. The volume of the fuel processor containing the atomizer, mixer, igniter, glow plug, ATR, steam generator and desulfurizer was 8 l (i.e. 0.3 ft<sup>3</sup>) and it weighed 5 kg. A brassboard prototype is being developed for integration with a power generating system.

## References

- [1] M. Lyubovsky, H. Karim, P. Menacherry, S. Boorse, R. LaPierre, W.C. Pfeifferle, S. Roychoudhury, *Catal. Today* 83 (2003) 183–197.
- [2] M. Lyubovsky, S. Roychoudhury, Novel catalytic reactor for oxidative reforming of methanol, *J. Appl. Catal. B: Environ.* 54 (2004) 203–215.
- [3] M. Lyubovsky, S. Roychoudhury, R. LaPierre, Catalytic partial oxidation of methane to syngas at elevated pressures, *Catal. Lett.* 99 (2005) 113–117.
- [4] S. Roychoudhury, M. Lyubovsky, Shabbir Ahmed, et al., Microlith catalytic reactors for reforming iso-octane-based fuels into hydrogen, *J. Power Sources*, 152 (2005) 75–86.