Partial Oxidation of JP8 in a Well-Insulated Distributed Reactor

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Abstract

10 Low temperature fuel reforming via partial oxidation in a distributed reactor has shown superior performances compared to other lower temperature approaches. Previous results and literature indicated higher reactor temperatures to yield superior results. The well-insulated reactor developed incorporated elements of the low temperature reactor design. The syngas obtained was of better quality in terms of gas species
15 component present and the syngas heating value than that reported previously from a non-catalytic reformer. The syngas composition consisted of 19.2% hydrogen and 20.8% carbon monoxide and these values are higher than the previously reported data. Lower series of
20 hydrocarbons (acetylene and propane) were only detected in trace amounts (less than 15 ppm). Elevated reactor temperatures promoted the dissociation of lower series of hydrocarbons (methane, acetylene, and

ethylene), which provided additional syngas formation. The gas species concentrations obtained approached that of catalytic reforming. Flame regime was determined through numerical diagnostics. As reaction regime became less distributed with higher injection temperature, reformate quality was adversely impacted. The mitigation of thermal losses from the well-insulated reactor promoted superior reformer efficiency by allowing the reactor to achieve conditions not possible in low temperature reactors.

1.0 Introduction

Reforming is the chemical decomposition of hydrocarbon fuels into syngas (primarily hydrogen and carbon monoxide). Syngas produced can be directly utilized in a fuel cell or other applications. Fuel cells are attractive as they provide enhanced efficiency for mobile power applications over conventional internal combustion engines. The fuel cells use hydrogen as the input fuel. However, hydrogen is not naturally available and is challenging to store. Reforming allows for hydrogen to be produced and utilized when and where it is needed. Currently, approximately 95% of all hydrogen is derived from steam reforming of natural gas[1]. Liquid hydrocarbon fuels have higher volumetric energy density than either liquid or compressed hydrogen. Therefore, the use of liquid fuels to produce hydrogen is of significant interest in many power and propulsion applications.

Logistically it is more desirable to reform hydrocarbon fuels, than utilizing liquid or compressed hydrogen. In addition, certain users such as the United States Army are logistically restricted to a mandatory fuel. The United States Army is required to use Jet Propellant 8 (JP8), which
5 can have concentrations of sulfur up to 3000ppm. Sulfur concentrations of this magnitude will damage most reforming catalyst. A non-catalytic approach is more suitable and was selected as it is unaffected by the sulfur present in the fuel. In a system, a gaseous phase desulfurizer will be required, but this is a more mature technology than liquid phase
10 desulfurization.

Fuel cells have different requirements of syngas composition. A proton exchange membrane (PEM) fuel cell requires high purity hydrogen (99.999%) but trace amounts of carbon monoxide will poison the fuel cell. A high temperature PEM fuel cell is more tolerant of carbon
15 monoxide, and is able to tolerate 4-5% carbon monoxide prior to irreversible damage. A PEM or high temperature PEM will employ a water gas shift (WGS) reactor to reduce carbon monoxide concentration and increase hydrogen content in the syngas. A solid oxide fuel cell can utilize hydrogen, carbon monoxide, and can internally reform methane.
20 Non-catalytic reformers typically produce syngas that is composed of higher concentrations of carbon monoxide and methane than catalytic reformation, which makes this reformer better suited for solid oxide fuel cell.

Previous non-catalytic reformer designs typically react in either porous media or in a heat exchanger. These approaches have yielded positive results, but each has its own prospective drawbacks. A porous media reduces volume of the reactor and a number of authors have cited damage to the ceramic foam [2–4]. In addition, Chen et al [5] found that material properties in heat exchanger based designs limit reactor conditions to less favorable temperatures than in porous media based reformers.

Fuel reforming in a distributed reactor can avoid these issues. Distributed reaction regime offers the ability to achieve stable reactions without the need for ceramic foam or heat exchanger. Reactor construction is simpler, as internal entrainment stabilizes the flame. This approach allows high temperature insulation to cover a simple pressure vessel constructed of stainless steel for enhanced durability and robustness.

In addition, the distributed reaction regime can enhance conversion of undesirable hydrocarbons[6]. Acetylene concentrations under distributed reaction regime were 75% lower than that under conventional flame reforming condition. The distributed reaction regime suppresses soot formation in the reactor in both combustion and reformation conditions. Soot formation downstream of the reactor was unaffected by distributed reaction regime. Hartman[7] indicated optimum reforming condition occur at 1000°C or greater which were not

achieved in previous low temperature work. Data reveals that reactor operation at higher temperatures would yield higher quality reformat, so that distributed reactor performance is expected to be superior at higher reactor temperatures. In this paper, partial oxidation of JP8 under a high temperature distributed reaction regime is explored and quantified.

2.0 Experimental Facility

2.1 Reactor

The reactor was comprised of a stainless steel pressure vessel (SS304) having internal volume of 0.926 L. High purity alumina insulation mixed with alumina binder coated the interior of the reactor. The insulated liner was 2.54 cm thick along inner walls of the chamber. The top and base of the reactor had 5.08 cm thick insulation, see Fig. 1. A high purity alumina (97%) is resistant to reduction by the syngas. Alumina is a common insulation in reformers and in catalyst support. In both applications, the alumina was unreactive. However, previous work on distributed combustor has used shock resistant silica bonded insulation[8]. Literature has shown shock resistant silica based binders to be easily damaged in reducing environment[9].

The reactor was enlarged by 5.08 cm over the previous design in order to increase minimum residence times of gases in the reactor to 380 ms[6]. The reactor was wrapped with heat tape and a secondary layer of 5.08 cm thick insulation. The heating tape allowed preheating the reactor to foster a faster startup. It also served to reduce thermal stress on the

insulation material. The heat tape was deactivated after ignition. A spark igniter located directly opposite to the central injector ignited the mixture in the reactor.

A premixed fuel-air mixture was injected into the reactor through a central location, having an inner diameter of 3.86mm. Prior to its injection, the temperature of premixed fuel-air mixture was measured. Reynold number in the nozzle was determined to be in the range of 3674 to 4190, which corresponds to an average residence time of 900 and 660 ms, respectively. Reformate was exhausted through two outlets on either side of the injector, located 3.02cm apart. The outlets had an inner diameter of 5.59mm. Dual outlets reduced the chances of any catastrophic failure in case of unwanted blockage in one of the outlets.

2.2 Test Bed

The test bed construction was similar in design to the previous work[6], but with modifications. Figure 2 shows a schematic of the test bed. Fuel and air were individually heated, prior to mixing in a four element static mixer. The mixer was enlarged compared to the previous work[6] to handle potential for steam vaporizer (not shown). Per manufacture, mixing efficiency was greater than 99.99% under the experimental conditions. Reformate from the two outlets of the reactor was ducted to a common exhaust. In addition, a liquid /vapor separator prevents unreacted fuel from escaping the test bed during ignition.

Jet Propellant 8 (JP8) used in the experiment had a heating value of 42.8 MJ/kg, and carbon content of 86.33%(mass). Sulfur concentrations were found to be approximately 150-160ppm. JP8 chemical composition on volume bases typically consists of 50-65% iso and normal alkanes, 10-20% cyclo-alkanes, 15-20% mono-aromatics, and 1-3% poly-aromatics hydrocarbons.

2.3 Instrumentation

Reformate concentrations were measured using an online four channel micro gas chromatograph. The gas chromatograph was capable of detecting fixed gases and lower hydrocarbons of up to C5 with an accuracy of 1.17% of reading. The gas chromatograph was calibrated against three primary standards with an analytical tolerance of 0.17% of measurement. The gas chromatograph sampled the exhaust stream every 3.2 minutes. Prior to the gas chromatograph, water vapor was removed with a condenser to prevent any damage to columns in the micro gas chromatograph. Carbon balance indicated 80%-93% detection based on the input fuel composition. Lower carbon balance corresponded with higher injection temperature. The undetected carbon was attributed to the observed soot formation in the exit stream.

Mean temperatures in the test bed and reactor were measured using K type thermocouples that were capable of withstanding to 1325°C. A thermocouple was placed in the center of the reactor, located between the center outer steel pressure vessel and secondary insulation.

Two thermocouples were placed 12.7 cm downstream of the exhaust.

Exhaust thermocouples were not a direct indicator of reactor temperature, but monitored for potential blockages. A thermocouple monitored the internal reactor temperatures. The thermocouple was positioned flush to the inner surface of the reactor to avoid flow obstruction. However, during ignition reactor temperatures exceeded thermocouple temperature of 1325°C.

3.0 Results and Discussion

3.1 Reactor Modes

10 The reactor showed two distinct operating modes during startup, which were determined from reformat composition and the reactor temperature profile. After ignition, for a period of 35 to 50 minutes, the reactor demonstrated unstable reformat concentrations and temperatures. This will be referred to as the first mode. After this time ,
15 reformat concentrations and temperature stabilized. This period will be referred to as second mode of operation.

 During start up the reactor was operated at O/C=1.25; excess oxygen reduces blockages and shortens the time to transition to the second mode. The primary work was chosen at O/C=1.0 due to the ideal
20 reforming conditions (sufficient reactants with no excess oxygen). The reactor was operated at 4.1kW_{th} with an oxygen/carbon (O/C) ratio of 1.25 at start-up. The feed stream was injected at 515°C. The fuel, preheated to 300°C, was injected at a flow rate of 5.79 g/min that allowed

complete fuel vaporization. Air, preheated to 600°C, was injected at 35.5g/min.

On startup the reactor underwent a transitional mode until the reactor stabilized, characterized by poor quality reformat. In this mode, the thermocouples located at the injector and exit gas stream showed elevated temperatures, while outer wall thermocouple showed decrease in temperature relative to the second mode, see Fig 3. Elevated injection temperatures were conjectured to be the result of heat conducted back through the nozzle. This indicates that the reaction zone occurs primarily at the front of the reactor. In addition, reformat quality was considerably reduced as compared to the later mode. The results shown in figure 4 shows reduced hydrogen and carbon monoxide concentrations, and elevated acetylene concentrations. The high acetylene concentrations, a known soot precursor, corresponded with visible smoke emission from the exit pipe.

Possible cause of the instability in the reactor were conjectured to be from the lack of thermal mass inside the reactor and the resulting need for the reactor to transition to thermochemical equilibrium. The lack of symmetry during ignition is attributed to hydrocarbon formation in exhaust lines. During startup, before sufficient entrainment could occur significant hydrocarbon formation occurred inside the reactor and exhaust line. The restriction in flow that resulted from the hydrocarbon deposits is attributed to biasing the exhaust to a particular outlet, that

contributed to lack of symmetry to cause slight differences between the two outlets. Uneven flow will result in a portion of the flow crossing the inlet, while oxidizing exhaust gases will result in elevated temperatures at front of the reactor. However, immediately after the start-up, the exhaust cleared itself with time resulting in a uniform flow, temperature and gas composition.

This was not observed in the previous work[6], which may be due to the larger size of the reactor vessel. Increased reactor size exacerbated this issue.

The flow and chemical reactions in the reactor stabilized after a period of approximately 20 minutes. The reaction zone detached from front of the reactor and distributed throughout the reactor. This is conjectured from decreased injection and exhaust gases temperatures, and a corresponding increase in wall temperatures, see Fig. 3. In addition, exhaust temperatures between the two outlets appear to equalize indicating equal flow through both the outlets. Figure 4 shows complete stabilization to occur after a period of 50 minutes. Hydrogen and carbon monoxide concentrations showed an upward trend with a corresponding decrease in hydrocarbons. Acetylene concentrations dropped below the detection level of 10 ppm. The drop in acetylene concentrations, a known soot precursor, corresponded with visible disappearance of smoke emission from the exit pipe.

3.2 Injection Temperature

The reactor was operated at 5.1kW_{th} , at a fixed oxygen to carbon ratio of unity. Fuel and air were operated at fixed flow rates of 7.08 g/min and 35.5g/min, respectively. Air preheats were used to control the injection temperature. Injection temperatures, measured prior to injection into the reactor, ranged from 383 to 556°C. Fuel was vaporized at constant 300°C. To prevent fuel condensation after vaporizer, lower injection temperatures were limited to 383°C. The reactor stability was determined from the observed reactor temperatures and reformat's concentration.

3.2.1 Flame Regimes

The flame regime was determined through numerical simulations, as the reaction zone was unobservable. Previous work has shown strong capability of predicating the emergence of distributed reaction regime[10], with a comparable design. Under condition tested shown in figure 5, reactions only occurred under the distributed reaction regime. Numerical simulation indicated that increasing injection temperatures resulted in a less distributed reactor, as experimental conditions transitioned away from distributed reaction regime. Increased injection temperatures fostered conditions that accelerated laminar flame speed and shortened laminar flame length.

A borghi diagram presented in figure 5, demonstrates the relevant flame regimes against Damkohler number(Da) and Turbulent Reynolds number(Re_o), see eq. 1 and eq. 2. The Damkohler number(Da) represent

the ratio between the characteristic mixing time scale to characteristic chemical time scale. Turbulent Reynolds (Re_o) is based on integral length scale(l_o) as given by Glassman[11] and Law[12], see eq. 2. Flame regime is defined as the ratio between the laminar flame thickness (δ),

5 integral length scale(l_o), and kolmogorov length scale(l_k). Distributed flame regime occurs at Da less than one and when δ exceeds l_o [13]. The upper limit of the distributed reaction regime, known as damkohler criterion, occurs when δ equals l_o . Conditions that exceed damkohler criterion are associated with the flamelets in eddies and wrinkled flames

10 regimes. Flamelets in eddies regime occurs when δ is less than l_o , but greater than l_k . The wrinkled flame regime occurs at Da greater than one and when δ is less than l_k .

Integral length scale(l_o), kolmogorov length scale(l_k), and turbulence velocity (u') are functions of the volume averaged turbulent

15 kinetic energy (k) and turbulent energy dissipation (ε). These properties were directly calculated using a commercial CFD code (Fluent), see eq. 3-5. Kinematic viscosity (ν) is a function of working fluid properties.

The integral scales were found to be relatively constant (1.90mm), while the kolmogorov length scales were found to range between 0.44-

20 0.49mm. Turbulent velocity was found to be between 1.29-1.62 m/sec.

$$Da = \frac{\left(\frac{l_o}{u}\right)}{\left(\frac{\delta}{s_l}\right)} \quad (1)$$

$$Re_o = \frac{u' l_o}{\nu} = \frac{u' l_o}{s_l \delta} \quad (2)$$

$$u' = \left(\frac{2}{3}k\right)^{1/2} \quad (3)$$

$$l_o = \frac{\left(\frac{2}{3}k\right)^{3/4}}{\varepsilon} \quad (4)$$

$$l_k = \left(\frac{v^3}{\varepsilon}\right)^{\frac{1}{4}} \quad (5)$$

Numerical simulations converged until the residual values were
 5 below 10E-5. Arghode [14] found that the k-ε realizable viscous model
 would give strong agreement with experimental data. Second order
 solutions were employed to give increased accuracy. Reactor symmetry
 allowed simulation of a quarter of the reactor, which reduced the mesh
 size to 511k element.

10 Laminar flame speed was determined using Chemkin Pro[15].
 This code was used to estimate laminar flame thickness (δ) through the
 ratio of thermal diffusivity (α) to laminar flame speed (S_l), see eq. 6. A
 reduced kinetic mechanism was used along with a surrogate that was
 designed to predict the laminar flame speed[16]. This approach has been
 15 found to strongly predict reaction regime and the development of a
 distributed reaction regime[10]. A five component surrogate was used
 which has been previously shown to predict flame speed with high
 accuracy[17]. Laminar flame speed was found to be 9.9 to 22.5 cm/sec,
 while laminar flame thickness ranged between 2.02-4.12mm.

$$20 \quad \delta = \frac{2\alpha}{S_l} \quad (6)$$

3.2.2 Reformate Concentrations

Injection temperatures were found to alter the reaction regime, which influenced reformate quality. As the reactor became less distributed, due to an increase in injection temperatures, hydrogen and carbon monoxide concentrations were adversely affected, see Fig. 6. A less distributed reactor promoted hydrocarbon formation, see Fig. 7. Reformate composition changed rapidly as experimental conditions approached the damkohler criterion. However, carbon dioxide concentrations were not strongly influenced by injection temperatures or reaction regimes. The high concentration of carbon monoxide and low concentrations of carbon dioxide indicated complete mixing to occur.

Hartmen et al[7] have cited that optimum temperature for reforming of middle distillate fuel lies in the range of 1000-1100°C. Previous low temperature work indicated that under distributed reaction regime higher injection temperatures improved hydrogen content[6]. In that work, reactor conditions occurred at lower than optimum temperatures. As injection temperatures increased, reactor conditions occurred closer to optimum temperatures. This offset the negative impact of a less distributed reactor. In the current work, the reactor conditions were at or near the optimum temperatures. As injection temperatures rose, the negative effects of the reactor transitioning away from distributed reaction regime became more apparent.

Typically catalytic partial oxidation of JP8 yield concentrations have been reported to be 24% hydrogen and 24% carbon monoxide[18]. Syngas composition shown here approached that of catalytic reforming, consisting of $19.2 \pm 0.22\%$ hydrogen and $20.8 \pm 0.35\%$ carbon monoxide.

- 5 The non-catalytic literature[19] of a jet fuel shows hydrogen of and carbon monoxide concentrations of 14% and 19%, respectively. Hydrogen and carbon monoxide concentrations demonstrated in this work exceeded those demonstrated in low temperature reactors[6].

- Of the hydrocarbons detected, only methane was detected in
10 considerable amount. However, methane is a desirable hydrocarbon. Solid oxide fuel cells can internally reform methane, allowing direct utilization of methane by the fuel cell. Propane and acetylene were detected only in trace quantities (less than 15 ppm), see Fig. 7. Propane and acetylene concentrations were detected near the lower calibration
15 limit for the micro-GC (10ppm lower limit). In the low temperature distributed reactor [6] ethylene, ethane, and trace amounts of higher hydrocarbons(butane and hexane) were detected, but were not detected during the high temperature reactor work presented here. Literature shows that optimum reforming conditions occurred at higher reactor
20 temperatures [7]. Higher temperatures are associated with the dissociation of methane and other lower molecular weight hydrocarbons.

3.2.3 Reforming Efficiency

Reforming efficiency is defined as the ratio of the lower heating value of the syngas to the lower heating value of the fuel, see Fig. 8.

Reforming efficiency is presented for both solid oxide (Eq. 7) and water gas shift (WGS)/PEM fuel cell (Eq. 8). Increased injection temperatures caused the reactor to become less distributed, which decreased reformat quality. Decreased reformat quality resulted in a drop in reforming efficiency.

$$\frac{LHV(H_2+CO+CH_4)}{LHV(JP8)} = \eta_{Solid\ Oxide} \quad (7)$$

$$\frac{LHV(H_2+CO)}{LHV(JP8)} = \eta_{WGS/PEM} \quad (8)$$

Previous work on distributed reaction regime at lower reactor temperatures[6] have shown reforming efficiency (Eq. 7) on the order of 56-57% at comparable conditions. In this work, reforming efficiency ranged between 58-59%. Reforming at lower temperature provided 19-36% methane in the recovered energy, while it was only 1-2% of the recovered energy in current work. The higher reactor temperatures promoted the dissociation of methane, which generate higher concentrations of both hydrogen and carbon monoxide. In addition the reformat concentrations presented here are significantly better than that reported in the previous non-catalytic reforming studies[2,5,6]. Reforming efficiency for catalytic partial oxidation ranged from 75%-85%[18], but are susceptible to sulfur poisoning.

3.2.4 Numerical Simulation

Numerical simulation of distributed reaction regime was conducted using Chemkin Pro[15], through a series of one dimensional reactors. The reactor network consisted of adiabatic plug flow reactor with a recirculation loop. The splitter recirculated fifty percent of the exhaust flow (mass basis) back to the front of the plug flow reactor. The reactor pressure was set at 12 psi. At the front of the reactor, the fuel-air stream perfectly mixed with the exhaust. This approach has the advantage of finite residence time. Figure 9 shows the reactor network as constructed from Chemkin Pro.

Numerical simulation utilized a detailed kinetic mechanism for hydrocarbons between the range of C8 to C16 under combustion, pyrolysis, and soot formation conditions. This kinetic mechanism[16] was originally intended to model combustion conditions (equivalence ratios between 0.2 to 2.0 and at pressure between 0.08 to 50 atm), but was shown previously to be able to adequately predict reforming with Jet A/JP8 under reforming conditions in a porous media based non-catalytic reforming[20]. The model used was comprised of 13,532 reactions and 435 species.

The surrogate was composed of 70%(vol) dodecane, 10%(vol) decalin, and 20%(vol) toluene[21]. This surrogate represents all major hydrocarbon classes found in JP8; iso and normal alkanes, cyclo-alkanes and mono-aromatic compounds. This results in an average molecular

formula of $C_{10.1}H_{19.0}$ and a lower heating value of 43.06 kJ/kg. In previous work it was found that this surrogate and kinetic mechanism provided strong agreement with partial oxidation of Jet A/JP8 in a non-catalytic porous media based reformer [20,22]. However, surrogate
5 ability to predict laminar flame speed has not been verified.

Numerical simulations showed somewhat mixed agreement with the experimental data. At lower injection temperatures, the modeling was in strong agreement with the experimental data. Simulation over predicted methane formation, this could have been a result of an
10 incomplete kinetics mechanism. Steam reforming and dry reforming reactions are predicted to be active in reactor, but were not included in this mechanism. Previous work in numerical modeling of reforming also indicated this kinetic model over predicts the acetylene formation[22]. However, experimental and simulation agreement diverged with
15 increasing injection temperatures, see Figs. 10 and 11. The divergence is conjectured to be the result deviation from the initial perfectly mixed assumption.

Numerical simulation assumed fuel and air mixture would instantly mix with recirculated effluents at beginning of the reactor.
20 However, experimentally a finite amount time is required for mixing to occur. As injection temperature increased ignition occurred more rapidly, thus reducing the time for mixing. This results in the in a less thoroughly mixed reactor, which indicated a deviation from the perfectly mixed

assumption. This may be a limitation on the numerical simulation with Chemkin Pro, but may be resolved in computational fluid dynamics (CFD). However, a sufficiently small number of chemical kinetic mechanism that could be incorporated into a CFD model to accurately captured reforming behavior of JP8 is currently not available the literature. Reactions were minimized though the use of a high velocity mixer. Residence times in the mixer were estimated to be between 6-8ms. Temperature measurements after the mixer indicated no evidence of pre-ignition.

4.0 Conclusions

Partial oxidation of JP8 in high temperature distributed reaction regime was investigated in a well-insulated reactor, based on the original low temperature design[6]. The results presented here demonstrated the feasibility of a non-catalytic reformer ability to achieve a hydrogen rich reformate using a middle distillate fuel. Numerical simulations enhanced understanding of experimental conditions and trends.

The syngas obtained was of better quality in terms of product distribution, and approached that of catalytic reforming. Syngas composition demonstrated $19.2 \pm 0.22\%$ hydrogen and $20.8 \pm 0.35\%$ carbon monoxide. Literature has shown catalytic reformate is typically composed of 24% hydrogen and 24% carbon monoxide[18]. Previous non-catalytic approaches only yielded syngas that was at most 14% hydrogen and 19% carbon monoxide [19].

Higher reactor temperatures yielded higher quality reformat as compared to previous low temperature reactor[6]. Higher reactor temperatures promoted the dissociation of lower series of hydrocarbons (methane, acetylene, and ethylene), which provided additional hydrogen and carbon monoxide. Mitigation of thermal losses from the insulated reactor allowed higher reactor temperatures that were not possible in the previously low temperature reactor studies[10].

The interaction of reformat product distribution to injection temperature was of significant importance. Lower injection temperatures promoted conditions that favored the formation of better quality reformat. Numerical diagnostics indicated that the reaction regime became less distributed with higher injection temperatures, negatively influencing the reformat quality. Lower quality reformat negatively impacted reforming efficiency. Reformat quality changed more rapidly as reaction regime approached the damkohler criterion.

The reactor showed two distinct operating modes, which were determined from reformat composition and the reactor temperature distribution. On activation, the reactor entered at a transitional mode characterized by the reaction zone shifting towards the front of the reactor and poor quality reformat. After a period of 20 minutes, the flow and chemical reactions stabilized and the reactor transitioned to a more stable secondary mode. Under these conditions, the reaction zone shifted farther back into the reactor to generate improved reformat quality.

Numerical simulations showed mixed agreement with the experimental data. At lower injection temperatures, the agreement was strong, but diverged rapidly with increase in injection temperature. The discrepancy is conjectured to be a divergence from the perfectly mixed assumption. Numerical simulation assumed fuel and air mixture would instantly mix with recirculated effluent at beginning of the reactor. Experimentally as injection temperature increased, less time was available for mixing to occur, as higher temperatures fostered faster reactions. This resulted in a less thoroughly mixed reactor, which indicated a deviation from the perfectly mixed assumption.

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Figure 1. A schematic diagram of the reactor

Figure 2. A schematic diagram of the test bed

Figure 3. Reactor temperature profile after ignition.

Figure 4. Reformate concentrations at $O/C=1.25$

Figure 5. Flame regime at $O/C=1.0$ at injection temperatures of $383-556^{\circ}\text{C}$

Figure 6. Concentration of fixed gases at $O/C=1.0$, at injection temperatures of $383-556^{\circ}\text{C}$

Figure 7. Concentration of Lower hydrogens gases at $O/C=1.0$, at injection temperatures of $383-556^{\circ}\text{C}$

Figure 8. Reforming efficiency of solid oxide fuel cell and water gas shift/ PEM fuel cell.

Figure 9. Chemkin simulation of distributed reactor.

Figure 10. A comparison of hydrogen and carbon monoxide concentration between numerical simulations and experiments.

Figure 11. A comparison of methane and acetylene concentrations between numerical simulations and experiments.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11