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International Journal of Hydrogen Energy 30 (2005) 1483 – 1490

International Journal of HYDROGEN ENERGY

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# On-board fuel processor modelling for hydrogen-enriched gasoline fuelled engine

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## Abstract

Hydrogen as a fuel for automotive engines is generally coupled with advanced conversion systems (fuel cells) but, due to energy crises and environmental pollution, hydrogen fuelling of internal combustion engines is of great interest as well.

In the near-term, the use of hydrogen as gasoline additional fuel in ICE is a very interesting and accredited approach. However the employment of hydrogen introduces problems in the fuel distribution and storage systems. These drawbacks could be overcome by using on-board hydrogen production systems.

In this paper, a numerical model of a simple reforming system, based on a partial oxidation process, has been developed. The model has been tested using the experimental data of a plasma-assisted reformer. The conversions of methane, propane, heptane, toluene and gasoline to hydrogen have been investigated and a thermodynamic analysis of the reforming system has been conducted by means of the AspenPlus software. The efficiency of the reformer/engine system has been also evaluated.

*Keywords:* Partial oxidation process; Thermo-chemical simulation; Reformer/ ICE system

## 1. Introduction

The interest in producing hydrogen on-board vehicle by means of reforming systems concerns the hydrogen utilization in internal combustion engine fuelling with gasoline–hydrogen lean mixtures [1].

In fact, small hydrogen mass flows can be produced on-board vehicles by means of hydrocarbon reforming systems by overcoming problems such as storage, transportation and, above all, distribution.

Using hydrogen-enriched gasoline in internal combustion engines could be very interesting. In fact, premixed charges, based on gasoline enriched with small amounts of hydrogen, are characterized by wide flammability limits and a high flame velocity leading to a high thermal efficiency, good engine performance and reduced pollutant emissions [2,3].

In a previous work [4], different operating conditions of an engine fuelling with very lean hydrogen–gasoline mixtures at the unthrottled operation have been analysed. The idea is that hydrogen can allow the leaning of the gasoline–air mixture in order to vary the engine load by varying the fuel flow rate as in a diesel engine. Furthermore, considering the possibility of using an on-board hydrogen generator, the overall fuel consumption of the hydrogen–gasoline engine has been calculated [5]. The on-board hydrogen production unit has to satisfy many requirements such as efficiency, compactness, weight and simple plant displacement. These requirements can be satisfied because auxiliary systems that reduce CO concentration, such as water gas shift and preferential oxidation reactors, might not be necessary; in fact, carbon monoxide burns in the internal combustion engine without any problems. For these reasons, in the present work a compact and simple reforming system has been studied and modelled using a thermo-chemical model.

This system (called GlidArc plasma) is a non-catalytic reformer based on high-voltage discharges that assists the

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doi:10.1016/j.ijhydene.2004.12.006

**Nomenclature**

| | |
|---|---|
| $n$ | number of moles |
| LHV | low heating value |
| $L_i$ | indicated engine work |
| $m_{\text{fuel}}^{\text{R}}$ | reformer fuel mass flow rate |
| $m_{\text{fuel}}^{\text{ADD}}$ | additional gasoline mass flow rate |
| $m_{\text{syngas}}$ | syngas mass flow rate |
| $m_{\text{fuel}}$ | gasoline engine mass flow rate |
| $\eta_{\text{R}}$ | reformer efficiency |
| $\eta_{\text{Engine}}$ | gasoline engine efficiency |
| $\eta_{\text{engine}}^{*}$ | hydrogen–gasoline engine efficiency |
| $\eta_{\text{System}}$ | reformer/engine system efficiency |
| $O/C$ | air ratio |
| $A$ | heat transfer surface of the reformer |
| $U$ | heat transfer coefficient |

exothermic partial oxidation (POX) process using air as oxidant [6]. The choice of studying this reformer depends on its characteristics which are rapid response time, no sensitivity and degradation of the catalyst and its small size.

## 2. Hydrogen production by reforming systems

Reforming processes are represented by steam reforming, POX and autothermal reforming. The first is more suitable to a stationary system rather than a mobile system because of its slow start-up. The steam reforming reaction is an endothermic reaction and requires heating (more fuel consumption). Furthermore, it is able to produce a high hydrogen concentration in the reformed gas, about 70% [7]. Therefore the efficiency of hydrogen production is high. However, the steam supply of the reactor is a problem for mobile systems.

The second and the latter offer a faster start-up time and a better transient response. These processes, although they do not require external heating, produce a lower hydrogen concentration in the reformed gas [7]. In fact, both POX and autothermal reforming involve a dilution of the hydrogen with nitrogen (air is used as an oxidant) and the hydrogen concentration is about 35% in volume. There are some additional problems when the reformed gas is used in an internal combustion engine as additional fuel to gasoline since it involves a reduction of volumetric efficiency.

In a previous paper [5], steam reforming and autothermal reforming systems have been studied and modelled by using the ASPEN-PLUS software. In the present work, the POX process has been studied and a non-catalytic reformer has been modelled. The model validation has been conducted using experimental tests [8,9].

In the following, some of the simulation hypotheses are listed.

- The reformer is assumed at the thermodynamic equilibrium and the reformed gas composition is calculated using the method of minimizing the Gibbs free energy [10].
- The possible species that might be found in the reformed gas are: $N_2$, $CH_4$, CO, $CO_2$, $H_2O$, $H_2$.

The simulation has been run with a Gibbs reactor because of insufficient kinetic data (reaction rates, residence time, known intermediate species, etc.) necessary to execute a plug reactor simulation. In fact, by applying this simulation method, individual reactions are not required because it is sufficient to define the components of the mixture produced. To analyse the operating condition of the reforming system, the air ratio ($O/C$) parameter is defined:

$$(O/C) = \frac{n_{O_2}}{n_{\text{fuel}}} \bigg/ \left(\frac{n_{O_2}}{n_{\text{fuel}}}\right)_{\text{complete\_combustion}}. \qquad (1)$$

The reformer efficiency has been calculated by considering both hydrogen and carbon monoxide in the synthesis gas. The efficiency is expressed by the following equation:

$$\eta_{\text{R}} = \frac{m_{\text{syngas}}\text{LHV}_{\text{syngas}}}{m_{\text{fuel}}^{\text{R}}\text{LHV}_{\text{fuel}}}. \qquad (2)$$

## 3. Simulation model: results and discussion

In this paper, a numerical model has been developed to reproduce the operating conditions of a plasma reactor that assists the exothermic POX of hydrocarbons (gaseous or liquid). In fact, the model has been validated by simulating the operation of the plasma reactor developed at the University of Orleans (France) by Prof. A. Czernichowski's research group. In works [8,9] test conditions and experimental results by varying the type of fuel are described. The reformer operating conditions and the experimental results [8,9] are listed in Table 1. These operating conditions are applied to propane and methane and to two values of the $O/C$ parameter for each fuel. The simulation model is shown in Fig. 1.

Fuel is fed into the reactor, combined with air in a fixed $O/C$ ratio, and converted into syngas. The thermodynamic analysis of the reforming system (Fig. 1) has been performed using the Gibbs free energy minimization method. In fact, the lack of detailed kinetic data has deterred a kinetic