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Rich *n*-heptane and diesel combustion in porous media

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ABSTRACT

Rich *n*-heptane and diesel flames in two-layer porous media are experimentally investigated in the context of syngas production. The stable operating points of *n*-heptane reforming have been determined and the mole fractions of H_2, CO, CO_2 and light hydrocarbons have been measured in the exhaust gas at an equivalence ratio of 2 for different thermal input values. The reformer performance has been assessed also from the point of view of the heat losses and the mixture homogeneity. The pre-vapouriser produces an approximately uniform vapour–air mixture upstream of the flame front. The range of flow rates for stable flames decreased with increasing equivalence ratio. Heat losses were about 10% of the thermal input at high firing rates. A 77.2% of the equilibrium H_2 was achieved at a flame speed of 0.82 m/s. The same reactor with a different porous matrix for the reforming stage demonstrates diesel reforming to syngas with a conversion efficiency of 77.3% for a flame speed of 0.65 m/s.

1. Introduction

Partial oxidation (rich combustion) of liquid fuels is a promising technique for hydrocarbon reforming in syngas. Syngas may be a source of hydrogen for fuel cells after a clean-up stage; it may be used for enrichment for traditional combustors, or as a way to produce a high quality fuel from a low energy content feedstock or from carbon neutral sources (biodiesel, vegetable and waste oil). Liquid fuels have the advantage of well-developed extraction, refining and distribution facilities. Furthermore, liquid fuels have the benefit of easy handling and high-energy content. Traditional reforming techniques such as steam reforming, catalytic partial oxidation and autothermal reforming involve expensive and delicate noble metal catalyst. Hot spots and ease of poisoning make catalytic reactors highly selective to the feedstock and reduce the robustness of the system [1].

This work is based on the principle of the thermal partial oxidation of *n*-heptane. The reforming process is carried out through the recirculation of the sensible enthalpy of the burned gases from the flame zone to the preheating section, by means of a porous medium. The preheating of the reactants allows higher flame speeds, local temperature higher than the adiabatic temperature and consequently faster kinetics. This "superadiabatic" effect results in the stabilization of rich flames beyond the flammability limits of the mixture [2]. This process has been previously demonstrated with various fuels (methane, methanol, and octane) [3].

The novelty of this work consists of the stabilization of steady rich pre-vapourised *n*-heptane and diesel flames inside a two-layer porous inert matrix and the exploration of reforming efficiency, extending hence the work of [3] towards real liquid fuels. Applications include small-scale reforming in the automotive and aviation sectors and for portable fuel cells. Previous work on *n*-heptane non-catalytic partial oxidation was based on filtration combustion in porous media [4], which may have the disadvantage of a more complex fluid handling system. Stabilised flames, on the other hand, are easier to control. Diesel reforming has been performed through steam reforming [5–7], catalytic partial oxidation [8,9] and auto thermal reforming [10], with very limited work on thermal partial oxidation. The principle of using two-layer burners, which allows stabilization over a wide operating range, was demonstrated in the past by several authors [12,13,16] for both liquid and gaseous fuels for lean combustion. Stabilised ultra lean *n*-heptane flames in two-layer burners have been demonstrated in [13], but rich flames have been studied little.

2. Experimental methods

The burner (Fig. 1) has a two-layer porous structure, the first of which assists evaporation and does not allow the flame to propagate upstream, while the second (downstream) layer is where the reforming occurs. The first layer is a flame holder and it consists of a 50 mm long packed bed of 3 mm Al_2O_3 beads. On top of this first layer, a 100 mm long 10 ppi ceramic (SiC, Al_2O_3, SiO_2 compound) foam is placed. The burner itself is a 70 mm ID stainless steel tube, 350 mm in length. The foam is wrapped in alumina paper, whereas the beads are poured inside the tube. In the optimum

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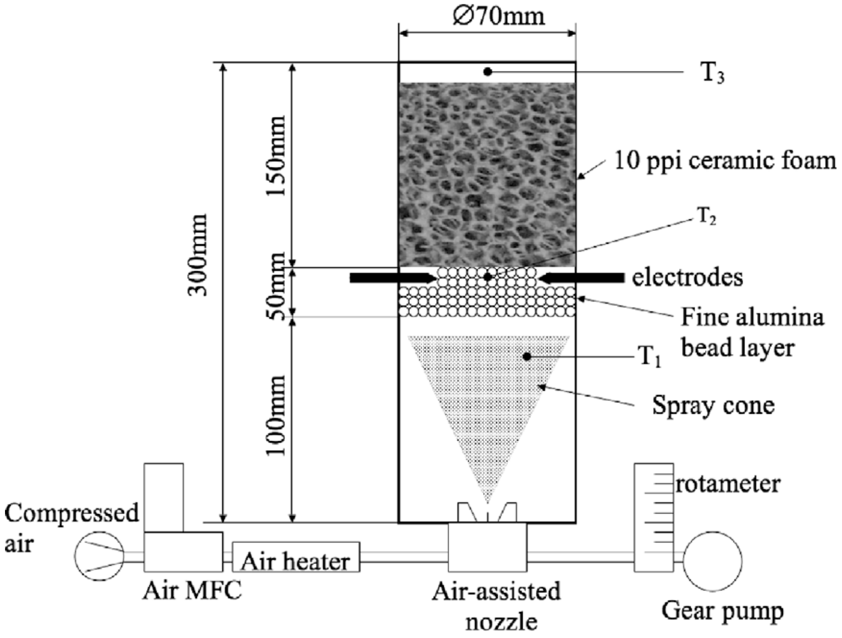

Fig. 1. Equipment setup.

condition, the flame sits at the interface of the two layers and the reaction zone extends into the foam. Diesel flames were also investigated in the same burner equipped with a 100 mm 20 ppi long MgO stabilized ZrO_2 foam for the reforming stage. Foam specifications are summarised in Table 1.

The liquid fuel is delivered through an air-assisted commercial nozzle (Delavan AL15 external mix nozzle). The fuel flow is controlled by a magnetic driven gear pump and a calibrated rotameter and reaches the atomizer at 1.1 bar. The flow rate measurement uncertainty is about ±5%. The air flow to the nozzle is controlled by a Bronkhorst Mass Flow Controller to an uncertainty of about ±2.5% and an air heater and reaches temperatures up to 300 °C. This air ensures atomization, subsequent evaporation because it is heated, but also provides all the oxidizer. The spray flows in a conical section 100 mm long and the evaporated fuel–air mixture reaches the first porous layer. A thermocouple placed just before the upstream side of the first porous section (i.e. at the end of the atomiser–vapouriser conical section) gives the voltage feedback to the air heater through a temperature controller (T_1). Two R-type thermocouples detect the temperature at the layer interface (T_2) and the gas temperature after the foam (T_3) respectively.

On the top of the burner a water-cooled probe allows the collection of a sample of the exhaust gas. Subsequently, the sample is passed through an ice bath for the condensation of the water content and then injected into a gas chromatograph (GC). The GC is equipped with a Thermal Conductivity Detector (TCD) and a Flame Ionization Detector (FID). The Molecular sieve and Haysep N porous polymer columns embedded in the GC oven can separate permanent gases such as H_2, O_2, N_2, CO and CO_2 and hydrocarbons up to C_2 (methane, acetylene, ethylene and ethane). The machine is calibrated by a gas mixture with species concentrations similar to the one expected. The uncertainty associated with the GC is at least ±2% which is the uncertainty assessed for the calibration gas by the supplier company (Scientific & Technical Gases Ltd.). Furthermore, the sample line is periodically checked for leaks and the samples are injected at the same temperature and pressure. Fig. 1 presents the sketch of the entire system. The quality of the air–vapour mixture leaving the conical pre-vapouriser section is tested without combustion by sampling across the burner and directing the sample to an exhaust emissions FID analyser (Cambustion Fast FID HFR500).

Table 1
Ceramic foam specifications.

Material	Commercial name	Porosity	Max. temp	Fuel
SiC, Al_2O_3, SiO_2	Vukopor S	10 ppi	1450 °C	*n*-Heptane
ZrO_2 MgO stabilised	Vukopor HT	20 ppi	1700 °C	Diesel

The test procedure starts from the warming up of the reactor by flowing only the oxidiser (i.e. the air) through the reactor to bring the temperatures up to 150 °C (300 °C for the diesel reforming tests) to avoid any condensation of the liquid fuel once injected. This first operation takes approximately 10 min (20 min for Diesel tests). At this point, the fuel is injected. An air/fuel ratio close to stoichiometry and a thermal power of 2 kW ("thermal power" means in this paper the mass flow rate of the fuel times its lower calorific value) is used first to achieve a prompt ignition by means of two ceramic-sheathed electrodes located at the interface between the two porous media. The ignition technique for the diesel reforming experiment is slightly different. Four automotive spark plugs are fixed on the burner in place of the two ceramic-sheathed electrodes. This latter system has the drawback of developing the flame in the very centre of the burner section, resulting in unburned diesel vapours crossing the peripheral area of the burner for 1–2 min. This would have a detrimental effect for any subsequent clean-up stage. Moreover, by placing the igniter in the hottest point of the burner (at the centre of the interface between the two porous layers) a rapid wear of the tips of the electrodes has been observed. The development of four flame kernels by the spark plugs reduce the time the flame needs to spread over the entire cross section of the burner, avoiding the emission of any unreacted mixture.

After the ignition, the reaction zone quickly extends inside the porous matrix and the equivalence ratio is switched to rich values.