ARTICLE IN PRESS

INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (2015) 1–7

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he

Investigation of rapid-starting strategy of cold start processing on porous medium-catalyst hybrid reformer

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ARTICLE INFO

Article history:
Received 17 January 2015
Received in revised form
12 March 2015
Accepted 27 March 2015
Available online xxx

Keywords:
Cold starting
Reforming
Hydrogen
Porous media

ABSTRACT

This study investigated the control strategy for the rapid cold startup process in porous media-assisted (PM-assisted) catalyst hybrid reformers that produce syngas from the partial oxidation of methane (CH_4). A control strategy was established based on the axial temperature distribution and infrared thermal imaging observations of the reformer under total oxidation reaction. In this study, methane was used to explore the temperature fluctuation characteristics exhibited by various fuels (CH_4 or H_2) during the startup process in reformer. Methane was also used to investigate operational strategies for achieving rapid cold-startup. The experiments confirmed that the rapid flame propagation speed and small quenching distance of hydrogen can shorten the startup time, reduce chemical energy supply, and provide superior thermal stability. The experimental analyses indicated that PM-assisted cold startups can improve the thermal stability of catalyst beds, reduce the temperature fluctuations in reformed gases, and effectively increase the reactive temperature of catalyst-packed beds.

Introduction

The characteristics of the worldwide energy industry have undergone substantial changes in recent years, during which gaseous fuels have become the mainstream fuel [1,2]. In addition to natural gas (NG) and liquefied petroleum gas (LPG), gaseous fuels include unconventional natural gas resources, such as biogas, landfill gas, and shale gas. The sources of these

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http://dx.doi.org/10.1016/j.ijhydene.2015.03.144

Please cite this article in press as: Lai M-P, et al., Investigation of rapid-starting strategy of cold start processing on porous medium-catalyst hybrid reformer, International Journal of Hydrogen Energy (2015), http://dx.doi.org/10.1016/j.ijhydene.2015.03.144

gases are highly diverse, but are primarily comprise methane and carbon dioxide [3]. If appropriately exploited, these gases can not only improve energy efficiency, but also mitigate greenhouse gas emissions. In recent years numerous studies have examined catalyst reformation and fuel-rich combustion to transform NG, LPG, and biomass-derived gas (BDG) into hydrogen-rich syngas [4]. The results can be employed for a wide range of applications, including chemical synthesis [5,6], blended engine combustion [7], and fuel cell power generation [8].

Furthermore, research teams around the world have employed porous media (PM) combustion chambers to enhance the flammability limits of fuels, in order to improve flame stability in fuel-rich combustion [9–11]. In these, the internal heat recirculation of PM is used to preheat reactants in reaction zones, thereby enhancing the oxidative heat released through combustion [12,13]. In the past few years this study's research team has proposed a PM-assisted catalyst bed design, and demonstrated that hybrid designs can improve flame position control and contribute to excess enthalpy reforming [14,15]. The proposed design can also substantially improve the efficiencies of fuel conversion and reformation in fuel processing. Despite the numerous advantages of PM-assisted catalyst bed designs, the heating rates of catalysts decrease when PM are placed upstream of catalyst beds, because PM possess high heat capacity and small pore structures. As a vital stage of the reformation process, the cold-startup time should be as short as possible to reduce fuel consumption and rapidly produce stable hydrogen-rich gas. Horng et al. [16,17] developed a methanol reformation startup procedure, which involves manipulating the air feed to control the heat released through oxidation. Cold-startup parameters were explored by adjusting the reactant preheat temperature, methanol feed rate, and the temperature of the steady state. The results confirmed that the shifting the temperature of the steady state affects both reformation performance and temperature response.

Changes in the PM combustion chambers during cold-startup processes have seldom been examined in the literature, and thus this study aimed to explore the parameters of rapid cold startups based on a PM-based catalyst hybrid bed design. The experiment exploited the advantages offered by hydrogen (e.g., no carbon sediment, rapid flame propagation speed, and low quenching distance) and used methane to explore the temperature escalation characteristics of various fuels in hybrid beds. The primary purpose of this study was to assess the operation strategies that facilitate rapid cold startups.

Experimental set-up and method

Establishing the experimental test platform

This study designed a hybrid reformer for syngas production using a combination of porous media and catalyst packed-bed. This design of PM-catalyst hybrid configuration offers a radial temperature uniformity and reactants preheating improvement. The experimental apparatus included a reformer unit, reactant supply system, arc generator unit, temperature data acquisition system and infrared thermal imaging device, as shown in Fig. 1. The reformer unit consisted of a mixing zone, preheating zone with PM, and a reforming zone with catalyst packed bed. The premixing chamber was used to increase the mixing of reactants with a swirling flow. Moreover, the case without PM is empty in preheating zone. The reformer unit was made of stainless steel. The total length of the preheating zone plus the reaction (Reforming + Emitter) zone was 69 mm, with an internal diameter of 50 mm. The distance between the igniter and the top of the porous media was 40 mm. The length of the mixing zone was 30 mm. The DC power supply was used to provide the power to the igniter in order to trigger reforming during the cold start, and it was shut down when the reforming began. The catalyst used in this study was made of Pt–Ru/Al_2O_3 (corundum-diamond structure), with a diameter of between 1 and 3 mm. The catalyst packed-bed was designed in a cylindrical form with a 15% porosity. The PM selected for the reformer was also cylindrical, with a height of 22 mm and diameter of 50 mm, and a composition of OBSiC ($SiC-Al_2O_3-SiO_2$). This has good thermal diffusivity and high thermal capacity. The porosity of the porous medium was between 80 and 85%, with 30 pores per inch. During the experiment, thermal imaging device (NEC TVS-200) were used to examine the temperature distributions with regard to the reaction chamber walls.

Experimental method

Catalyst coking and deactivation is likely to occur in carbon-rich and low-temperature conditions during the reforming reaction [18]. Therefore, cold start processing concerns the stability and catalyst activity in reforming reactions [19]. Additionally, shorter cold start processing times are superior, because they can reduce the fuel supply and accelerate the achievement of a stable hydrogen-rich gas output [20]. Therefore, this study divided cold starting into start-up procedure and the POX conditions. Cold starting uses combustion reactions ($\psi = 1$) to provide the heat required to initiate catalyst reactions. Without this, carbon formation at low temperature conditions can be avoided. The POX condition switches to methane partial oxidation reforming ($\psi = 4$) to maintain the catalyst bed reaction temperatures. After the temperatures stabilize, it adopts fuel processing parameters. This prevents the termination of the reaction because of insufficient heat in the catalyst bed. The POX condition transient transfer process can slowly increase reaction temperatures on the catalyst bed without damaging the catalyst. Therefore, cold start processing uses oxidative heat release to provide the heat required for reactions on the catalyst bed. This can eliminate external heating installations, which are complex and waste energy. Additionally, oxidative heat release can reduce the time required for cold start processing.

The combustion reactions in the starting process control the identical energy input (E = 1.6 kW) and equivalent ratio ($\psi = 1$). The converted methane feed flow rate was 3 NL/min and the hydrogen flow rate was 10 NL/min. The POX condition reforming parameters were a methane flow rate of 10 NL/min and an O_2/CH_4 ratio of 0.5 ($\psi = 4$). OBSiC with excellent thermal shock resistance was selected for the PM on the upper reaches