Egyptian Journal of Petroleum (2014) 23, 79–86

Egyptian Petroleum Research Institute

Egyptian Journal of Petroleum

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FULL LENGTH ARTICLE

Fuel rich and fuel lean catalytic combustion of the stabilized confined turbulent gaseous diffusion flames over noble metal disc burners

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Received 19 June 2013; accepted 28 October 2013
Available online 19 March 2014

KEYWORDS

Catalytic combustion;
Fuel-rich;
Fuel lean;
Noble metal burners;
Thermal structure;
Oxidation products

Abstract Catalytic combustion of stabilized confined turbulent gaseous diffusion flames using Pt/Al_2O_3 and Pd/Al_2O_3 disc burners situated in the combustion domain under both fuel-rich and fuel-lean conditions was experimentally studied. Commercial LPG fuel having an average composition of: 23% propane, 76% butane, and 1% pentane was used. The thermal structure of these catalytic flames developed over Pt/Al_2O_3 and Pd/Al_2O_3 burners were examined via measuring the mean temperature distribution in the radial direction at different axial locations along the flames. Under-fuel-rich condition the flames operated over Pt catalytic disc attained high temperature values in order to express the progress of combustion and were found to achieve higher activity as compared to the flames developed over Pd catalytic disc. These two types of catalytic flames demonstrated an increase in the reaction rate with the downstream axial distance and hence, an increase in the flame temperatures was associated with partial oxidation towards CO due to the lack of oxygen. However, under fuel-lean conditions the catalytic flame over Pd catalyst recorded comparatively higher temperatures within the flame core in the near region of the main reaction zone than over Pt disc burner. These two catalytic flames over Pt and Pd disc burners showed complete oxidation to CO_2 since the catalytic surface is covered by more rich oxygen under the fuel-lean condition.

1. Introduction

Catalytic combustion or heterogeneous combustion had been extensively investigated in recent years. The catalytic oxidation of hydrocarbons became the focus of much basic and applied catalysis research because of its increasing importance for burner's design of industrial furnaces and the techniques of power-generating gas turbines [1,2]. For these applications, high temperature catalytic combustion was regarded as highly efficient and clean energy system. It had been recognized that

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Peer review under responsibility of Egyptian Petroleum Research Institute.

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noble metals possessed the highest catalytic activities that initiated the catalytic oxidation of fuels at relatively lower reaction temperatures [3,4].

Many experimental investigations reviewed the effect of using noble metals in the catalytic combustion domain. In a confined turbulent flame the effect of using Pt/γAl_2O_3 catalytic disc burner was examined at different axial distances over the fuel jet nozzle [5]. This investigation revealed how the highly efficient oxidative exothermic reactions in contact with the active surface of platinum burner greatly enhanced the heat evolved via catalytic ignition and hence, improved the stabilization tendency to a great extent. Also, the progress of the combustion process over the platinum sites had controlled the combustion emission products therefore minimizing the environmental pollution. Moreover, Appel et al. investigated the catalytically stabilized turbulent combustion of fuel-lean hydrogen/air pre-mixtures over platinum and found that nearly half of the fuel was converted heterogeneously and the remaining part was combusted in the post-catalyst [6].

More recently, the catalytic combustion of different hydrocarbon fuels over platinum addressed the interaction between homogenous and heterogeneous reactions. The experimental study revealed that in the presence of platinum the reactions are complex and highly dependent on the fuel used as well as other parameters such as temperature, equivalence ratio and Reynolds number of the gaseous fuel–air mixture [7]. Furthermore, the effect of catalytic combustion of gaseous turbulent diffusion flame over a series of noble metal disc burners (Pt, Pd and Pt + Pd) supported on γAl_2O_3 were experimentally and mathematically studied [8]. These catalytic flames behave in highly catalytic conditions and their catalytic enhancement was found to be in the order: (Pt + Pd) > Pt > Pd. The thermal distribution along these catalytic flames recorded high values due to the enhancing of fuel oxidation on the noble metal sites in the reaction zone of the flame via improving homogenous gas/heterogeneous surface reactions in the combustion domain.

Fuel-rich catalytic combustion had been investigated in order to demonstrate the successful technology of ultra-low emissions for gas turbine which in the mean time, offered multiple advantages, [9–12]. The catalytic combustion of methane under lean and rich conditions over platinum and palladium catalysts was investigated using dilute mixtures [13]. It had been found that under lean conditions Pd was the more effective catalyst. Pt containing catalysts had been found to be more active as the reactant mixture was shifted from oxygen–rich to methane–rich. The platinum catalysts were superior to palladium in a fuel-rich gas mixture. Thus, platinum had a role as a component in the catalyst for emission control of natural gas vehicles. Also, the performance data of catalytic combustion were presented for methane oxidation over platinum group catalysts under fuel-rich and fuel-lean conditions [14]. These authors found that under fuel-lean conditions, Pd catalyst was the most active, although deactivation occurred above 650 °C. While under fuel-rich conditions, Pt catalyst was more active above 600 °C and acquired much higher activity of the reaction rates through the catalytic combustion domain.

A rich catalytic lean burn combustion system was developed for the operation of natural gas as fuel and other non-methane fuels [15]. For fuel-rich operation the reactor performance was insensitive to the fuel reactivity, because the reaction rate (heat release) upon the catalyst surface was controlled primarily by the oxygen mass transfer to the catalyst under fuel-rich condition and not by the fuel flow or the fuel reactivity for all the fuels tested.

For methane or natural gas fuels, the catalyst activity was significantly improved by operating the catalyst under fuel-rich conditions as compared to fuel-lean conditions and therefore, allowing a wider choice of catalyst materials. Fuel-rich methane combustion over Rh-La-MnO_3 honeycomb catalysts was developed as a preliminary conversion step in advanced combustion system such as power turbine and utility burners for reducing emissions [16]. The experimental results showed that mixed Rh-La-MnO_3 catalysts were suitable for the fuel-rich applications. However, a progressive reduction of light-off temperature and a parallel improvement of the catalytic partial oxidation performance were observed by increasing Rh content in the Rh-La-MnO_3 catalysts.

The present work investigated the effect of using Pt/γAl_2O_3 and Pd/γAl_2O_3 catalytic disc burners situated in the combustion domain of confined turbulent stabilized gaseous diffusion flames under fuel-rich and fuel-lean conditions. The thermal structure of these catalytic flames developed over Pt and Pd catalytic disc burners was examined by measuring the mean temperature distribution in the radial direction at different axial locations along the flames. Also, the axis–symmetric distributions of CO and CO_2 along the flames were monitored under the same conditions to clarify the catalytic combustion process performance over the two current catalytic discs.

2. Experimental

The experimental setup (Fig. 1) was comprised of a vertical cylindrical combustion chamber filled with an arrangement supplying fuel and air. The combustion chamber (Fig. 2) is 150 mm in diameter, 5 mm thick and 1.0 m long. The combustor was equipped with a thermal resistant glass window. The fuel jet was discharged vertically through a nozzle of 2.5 mm diameter connected at the centre of the fuel supply line in the axial direction at the base of the combustor. Commercial LPG fuel having an average composition of: 23% propane, 76% butane, and 1% pentane was used in all experiments.

Two catalytic disc burners of Pt and Pd over γ-Al_2O_3 having a diameter of 40 mm, 4 mm thick and perforated with 25 holes had been separately used as a catalytic flame burner. The discs were placed at the base of the combustor at the specified supporting distance of 40 mm over the fuel jet nozzle. These discs were made of γ-Al_2O_3 with a surface area of $60 m^2 g^{-1}$. Each Al_2O_3 disc support was made by mixing γ-Al_2O_3 powder with a suitable binder then pasted and formed. After drying at 110 °C overnight, the disc was perforated by drilling to acquire a suitable perforation (3 mm holes diameter). The disc was then calcined at 400 °C for 4 h. in a muffle furnace. The heat treatment gave the highest crushing strength while retaining the catalytic activity.

The 1st disc (Pt/ γ-Al_2O_3) was impregnated with H_2PtCl_6 solution such that the Pt content was 0.0001 wt% of the disc. The disc was again dried at 110 °C overnight and calcined at 550 °C for 4 h.

The 2nd disc (Pd/γ-Al_2O_3) was prepared via wet impregnation of an aqueous solution of Pd $(NO_3)_2$ containing 10^{-4} g of Pd metal. The impregnation was adjusted to incorporate the Pd containing solution on the external surface (1 mm depth).