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An experimental study of the effects of equivalence ratio, mixture velocity and nitrogen dilution on methane/oxygen pre-mixed flame dynamics in a meso-scale reactor

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ABSTRACT

At the present study, the effects of nitrogen dilution, equivalence ratio and inlet mixture velocity on methane–oxygen premixed flame dynamics in a meso-scale reactor with inner diameter of 5 mm has been investigated experimentally. The methane–oxygen premixed flame formation zones and also dynamical behavior of the established flames in a meso-scale reactor have been explored. In this research, the presence of five flame regimes of blow-off, blowout, normal asymmetric, repetitive extinction and re-ignition (RERI), and flashback have been observed. Based on the results of this study, it can be inferred that by increasing the inlet mixture velocity, the equivalence ratio should be decreased from fuel rich values toward the stoichiometric value for establishing the flame in a meso-scale reactor. In addition, it has been shown that by increasing the inlet mixture velocity more than a critical value, RERI type of flame may occur. Moreover, increasing the dilution percent at a constant flow rate of oxygen restricted the asymmetric stable flame region and simultaneously extended RERI and blowout regions for the various values of entrance mixture velocities versus equivalence ratio. On the contrary, decreasing the dilution percent (to lower than a critical value) could lead the flame to flashback. Also, it was shown that only the asymmetric flame could be formed as a stable flame in such a meso-scale reactor. Moreover, increasing the equivalence ratio to the fuel rich side moved the flame location toward the reactor outlet.

1. Introduction

During the recent two decades, combustion in meso and micro scales has been propounded as one of the most attractive research fields in the combustion science and technology. The importance of this research field is growing due to development of meso and micro scale reactors as energy suppliers, measuring systems for determining the combustion characteristics and also in situ measurement of the burning velocity of various combustible mixtures [1–3].

Moreover, there are fundamental and various disparities between the combustion process in meso/micro and macro scales. Due to high surface to volume ratio in meso or micro scale reactors (which typically reaches to about 2000 for a tube with 1 mm in radius), the flame thermal/radical quenching and the heat loss to the outer ambient are very significant. The complex of thermal/radical quenching and heat loss can impressively affect the combustion process and the dynamic behavior of flame in meso/micro scale reactors. Therefore, during the recent years, the most performed researches in this field have been focused on the mentioned topics, especially flame dynamics in meso/micro scales reactors.

In a research conducted by Lee and Maruta [4], they showed that a flame in a meso-scale tube has two length scales. These two length scales are corresponding to the ordinary flame and convective preheat zone thicknesses. Due to extreme heat recirculation between the post-flame and the preheating zones, the convective preheat zone is thicker than the ordinary flame thickness [4]. In another research performed by Ju and Xu [5], propagation and extinction of the premixed propane–air flames in meso-scale channel reactors have been studied experimentally, theoretically, and numerically. In this study, the effects of the wall heat losses and the wall-flame interactions are considered. The results of this research showed that the wall-flame interactions lead

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to multiple flame regimes and extinction limits. In this regard, the fast and slow flame regimes will be established in a meso-scale reactor by decreasing the channel width or equivalence ratio [6]. Also, they showed that the thermal coupling between the flame and the reactor wall is stronger at the higher mixture flow rates [5,6]. Moreover, Ju and Xu [6] showed that there are two flame regimes in a meso scale reactor for propane–air and methane–air combustion in which transfer between these two flame regimes is a function of the mixture flow rate [2,6]. Also, they investigated the effects of channel width, flame curvature, mixture flow rate and Lewis number on the propagation limits and the transition among the different flame regimes in a meso-scale reactor, experimentally and numerically [6]. The results of their studies showed that, the relationship between the flame velocity and equivalence ratio is not linear [5,6].

The dynamics of premixed flames and their structure in meso and micro cylindrical reactors, which are subject to the imposed external thermal pattern on the reactor wall, are extensively studied by Maruta et al. [7–9]. They studied the combustion characteristics of premixed flames in a heated cylindrical reactor in which its inner diameter was smaller than the conventional quenching distance [10]. They showed that four kinds of flame regimes can be seen in meso/micro scale reactors. These regimes are normal, repetitive extinction and re-ignition (FREI), oscillatory, and compound repetitive extinction and re-ignition-oscillatory flames. Also, they showed that the oscillatory flame instability occurs only in a reactor with subcritical diameter. In this regard, stable flames such as normal and weak flames have been observed in high and low mixture velocities, respectively [10]. In moderate mixture velocities, the dynamic behavior of the flame is mostly the same as FREI and pulsating regimes [10].

According to the literature [2], multistage oxidation processes of compression ignition could be equivalent with the various forms of stabilized flame in a meso/micro flow reactor. Therefore, this reactor could be used for studying the transient ignition process in the modern compression ignition engines [2]. In this regard, Hori et al. [11] investigated the ignition and combustion characteristics of a premixed primary gaseous reference fuel (PRF)/air flame using a micro reactor with the imposed external thermal pattern on its wall. They showed that it is possible to study the general ignition characteristics of various fuels using a meso/micro scale reactor. During this research, the presence of three flame regimes of weak, FREI, and normal have been reported.

In another work, Oshibe et al. [12] studied the ignition and combustion characteristics of a stoichiometric mixture of Dimethyl ether (DME)–air in a micro flow reactor. The micro flow reactor was subject to a controlled thermal profile on its wall in which its temperature increases smoothly from ambient temperature to the mixture ignition temperature. The main targets of this study were focused on the multistage oxidation process of DME/air mixture in low temperature conditions and also presenting the reactor as an instrument to validate the results of various applied chemical mechanisms under different temperatures of the inlet mixture. In the direction of the previous research, Nakamura et al. [13] studied the details of oxidation process of a stoichiometric mixture of ethanol–air and its pressure dependence based on the separated weak flames in a micro scale reactor, experimentally and numerically. They showed that in contrary to the methane–air combustion which has a reaction zone, ethanol–air combustion is comprised of the separated weak flames and also it can be oxidized at low temperatures [13]. Moreover, the combustion characteristics of gaseous and liquid fuels in a meso scale reactor equipped with a metallic wire mesh have been researched by Mikami et al. [14]. They reported the occurrence of two flame regimes of weak and normal in a meso scale reactor.

Furthermore, Evans and Kyritsis [15] studied the oscillatory behavior of extinction and ignition of fuel-rich, premixed methane/propane–oxygen flames in a meso scale reactor for determining the oscillation frequency modes of the flame as a function of equivalence ratio and inlet mixture velocity. During this study, they observed the formation of various types of stable and oscillatory flames. Also, they showed that the boundaries among methane–oxygen flame behavioral regimes are almost exclusively depended on equivalence ratio. Moreover, their results showed that extending the reactor length increases the stability of oscillations for both methane–oxygen and propane–oxygen flames. However, its effect on propane–oxygen flame was less prominent. Moreover, they maintained that the oscillatory extinction and re-ignition behavior can be seen only in meso scale reactors in which their wall thermal conductivity is low [15]. In other words, establishing the repetitive extinction and re-ignition flame regime is impossible in the reactors with high wall thermal conductivity and high thermal diffusion.

On the other hand, in an investigation conducted by Ju et al. [2,16], it is shown that the transition between the spinning and the stabilized planar flames can be controlled by external cooling or heating up of the meso scale reactor wall and consequently changing the flame-wall thermal coupling. Therefore, it is possible to control the flame instabilities by controlling the flame-wall thermal coupling [2,16].

Thus regarding to the importance of the effect of flame dynamics on the operation of a meso or micro scale reactor, the main scope of this research is focused on the study of the effective parameters on the dynamics of premixed methane–oxygen flames in a cylindrical meso scale reactor. Therefore, in the present study, the effects of inlet mixture velocity (as Reynolds number), mixing ratio between fuel and oxidizer (as equivalence ratio), and dilution on flame dynamics are studied. Also, the combustion characteristics of various reactive mixtures in a meso scale reactor have been evaluated during this study.

2. Experimental method

As can be seen in Fig. 1, a cylindrical quartz reactor with dimensions of 5 mm in inner diameter, 200 mm in length and 1 mm in the wall thickness was used as an experimental reactor. All the experiments have been performed at ambient temperature of 25 °C. In order to provide the required fuel and oxidizer, the high pressure pure methane (99.99%) and oxygen (99.95%) reserved in cylinders have been used. For measuring the fluid flow and pressure in the fuel and oxidizer lines, four digital flow meters (NewFlow and Yamatake) and two digital gauge pressure (NewFlow) with accuracy of 0.1% in the full scale range (measuring capacity) have been applied. Also, the on/off situation of the fluid flow and system safety in the fuel and oxidizer lines were controlled by the electrical and check valves at proper locations. All the applied fittings and pipes were union-nut style and cupric. In this study, the methane–oxygen mixture has been prepared before entering the reactor. The entrance mixture temperature was 300 K. Also, the reactive mixture was ignited by a proper igniter located at the exit of the reactor. In this regard, overall view and schematic flow diagram of the applied experimental apparatus with its measurement devices are shown in Fig. 1. In the experimental apparatus, the flame pictures and films have been captured by two digital still cameras, Canon Power Shot G6 and Nikon V1, respectively.

Furthermore, during the study, the flow velocity in the reactor was needed to be compared with the flame speed for every incoming reactive mixture to the reactor. In this regard, the flame speed (freely propagating) was calculated (Fig. 2) using a home-made