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Dynamic behaviors of premixed hydrogen–air flames in a planar micro-combustor filled with porous medium

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HIGHLIGHTS

- Premixed hydrogen-air combustion in a planar micro-combustor was studied.
- Flame stability limits for different combustor configurations were identified.
- Porous medium was found to be effective in enlarging the operation window.
- Blow-off limits are nearly independent of combustor configurations.
- Flashback limits are greatly influenced by the parameters of the porous medium.

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ABSTRACT

The micro-combustor is a key component of the micro-thermophotovoltaic (TPV) system, and the flame stability limits are very important to its design and operation. An experimental study on the dynamic behaviors of premixed hydrogen–air flames in an $H = 1$ mm planar micro-combustor is undertaken. The combustor is partially filled with porous medium to enhance heat transfer and flame stabilities. Critical conditions (Φ_1 for blow-off, Φ_2 for flashback, and Φ_3 for breaking through the porous medium) are experimentally identified for different combustor configurations. It is shown that the blow-off limits are nearly independent of the combustor configuration, while the flashback limits are strongly affected by the combustor configuration as well as the parameters of the inserted porous medium, including the position (L_{out}), the width (W) and the porosity (ε) of the porous medium. Most of the results can be explained by the classic boundary velocity gradient theory by von Elbe and Lewis in a qualitative sense. Based on the experimental findings, widening the operation window of the planar micro-combustor partially filled with porous medium is possible when the parameters are chosen properly.

1. Introduction

The inception of micro-combustion research can be traced back to the time when Epstein and Senturia [1] proposed the concept of the ‘micro heat engines’, followed by various prototypes of micro power generation systems, such as the micro gas turbine [2], the micro-thermoelectric generator [3], the micro-thermophotovoltaic (TPV) system [4] and many others. Most of the systems are based on hydrogen or hydrocarbon fuels. They were mainly motivated by the fact that hydrogen and most hydrocarbon fuels contain much more energy per unit mass than the most advanced lithium-ion batteries, therefore having a huge potential of miniaturizing the current power supply packages [5]. The recent progress in the research of micro-combustion and micro power systems is reviewed in Refs. [6–8]. It was pointed out that the understanding of fundamental flame behaviors and combustion characteristics in the micro- and meso-scale is still insufficient. This information is crucial for the appropriate design of the micro-combustors to be used in miniaturized power systems.

In the past years, many researchers have carried out experimental studies [9–25] on flame behaviors in micro-combustors to address the fundamental issues associated with the effects of the reduced combustor size on flammability, flame stability limits, flame temperature and so on. Those studies were aimed at achieving self-sustained flames in simple geometries such as cylindrical

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tubes [9–11], rectangular ducts or parallel plates [12–16] and radial channels [17]. In general, stabilizing flames in micro-combustors turned out to be a challenging task due to the strong thermal coupling between the flame and combustor walls, which has become an important subject for micro-combustion research. For this purpose, some methods like external heating [18,19], backward-facing step [20–22], catalyzed combustion [23], heat recirculation [24,25] and so on were employed. Among them, heat recirculation from the exhaust to the unburned mixture was shown to be effective in increasing the flame speed and extending flammability limits [26,27], suggesting the importance of transferring heat from the 'high temperature zone' to preheat the mixture in the context of micro-combustion.

In the development of the micro-TPV system, a planar micro-combustor partially filled with porous medium (stainless steel mesh) was proposed, fabricated and tested, finding that the thermal radiation from the combustor wall could be greatly enhanced against the case without porous medium [28,29]. This configuration essentially provides another path, in addition to the existing path (that is, the combustor walls), for enhanced heat transfer from the flame zone to the unburned mixture through the porous medium. It was noted that the higher wall temperature was attributed to the higher flame temperature resulting from the extended preheating length [30]. So far, however, the dynamic behaviors of the premixed flames inside the planar micro-combustor were not systematically analyzed. Therefore, as a follow-up of our previous studies [28,29], the purpose of the present study is to map the stability limits (mixture velocity U and equivalence ratio Φ) for different combustor configurations, which serves two-fold purposes: (1) to quantitatively identify the critical conditions, they are, blow-off and flashback, for the planar micro-combustor; and (2) to delineate the operation window for the applications of such a configuration.

Flame stability limits, an important topic in the combustion research, have been extensively studied for macro-scale combustors, and relevant theories have been established to explain the experiment results. Back in 1949, von Elbe and Lewis [30] first presented their theory of flame stabilization by introducing the boundary velocity gradient near the combustor rim, and since then that theory has been well validated by many experimental results. A more comprehensive experimental study was conducted by Grumer et al. [31] and their results covered a wide range of gaseous fuels, flow velocities and equivalence ratios. However, when it comes to the near-quenching dimensions, Yuasa et al. [32] found that the boundary velocity gradient theory could not explain the experimental results when the tube diameter is smaller than 1 mm. Having brought up this issue, it should be mentioned that it is beyond the scope of this study to discuss the validity of von Elbe and Lewis' theory in explaining the flame stability limits in the scenario of micro-combustion, and the focus is on presenting the experimental results and managing to use the existing boundary velocity gradient theory to analyze them in order to make some physical sense. In fact, it was already pointed out in Ref. [31] that the combustor size has a pronounced effect on the flame stability limits, especially the flashback conditions, but no references clearly defining under what conditions (for example, the critical combustor size) the boundary velocity gradient theory will fail and why it fails, have been found.

2. Experimental set-up and approach

The experimental set-up for the present study is schematically shown in Fig. 1. The whole system is exposed to the ambient air and not insulated. It consists of two pressurized gas tanks, two mass flow controllers, a mixing tank, a planar micro-combustor (with a flow connector), and an infrared thermal imager connected to a computer. Hydrogen is chosen as the fuel because of its high heating value, fast diffusion velocity, short reaction time and high flame speed [2]. The flow rates of hydrogen and air are adjusted using Seven Star® Mass Flow Controller (Model CS200-A) which is capable of controlling the flow rates accurate to less than 1% of the specified value. Hydrogen and air are fed to the mixing tank in which staggered steel plates are designed to lengthen the flowing path in order to achieve good mixing before entering the combustor. Fluke® Thermal Imager (Model Ti400) is mounted on a tripod and used to monitor the variation of wall temperature in the course of flame propagation, and also to assist to judge the existence of combustion upon ignition.

The micro-combustor and the connector (see Fig. 1) used in the experiment are made of stainless steel (SS) 316L which is able to withstand high temperature without significant degradation. Detailed design features and configurations of the planar micro-combustor are shown in Fig. 2. There are three configurations:

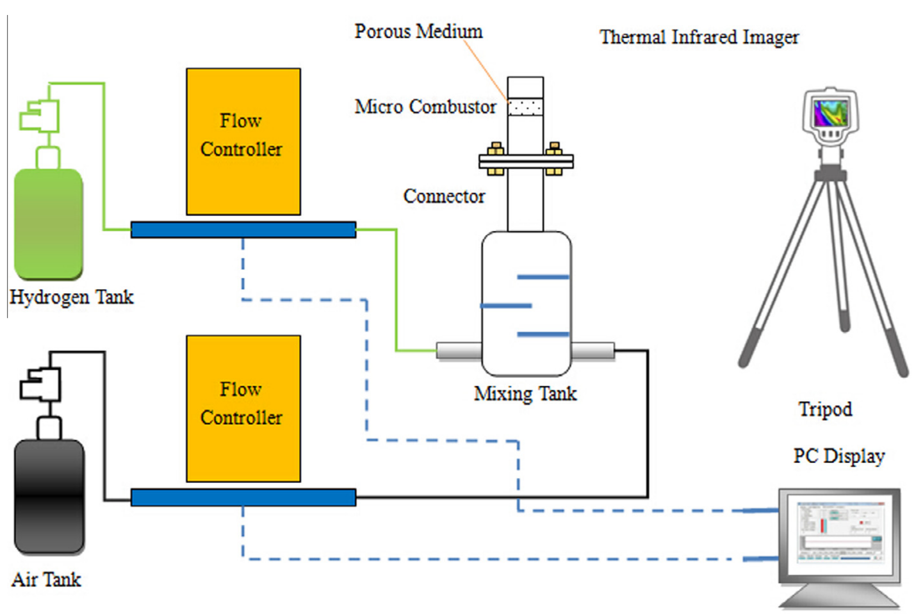

Fig. 1. Schematic of the experimental set-up.