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Scale and material effects on flame characteristics in small heat recirculation combustors of a counter-current channel type

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ABSTRACT

Small energy sources have been interested with the recent development of small-scale mechanical systems. With the purpose of developing a basic model of micro-combustors of heat recirculation, small combustors of a counter-current channel type were fabricated, and the premixed flame stabilization characteristics were investigated experimentally. Each combustor consists of a combustion space and a pair of counter-current channels for heat recirculation. The channel gap was less than the ordinary quenching distance of a stoichiometric methane-air premixed flame. Depending on the flame locations and structures, flame stabilization was classified into four modes: an ordinary mode, a channel mode, a radiation mode, and a well-stirred reaction mode. Base-scale combustors of stainless steel were initially examined. Additional half-scale combustors of stainless steel and quartz were fabricated and their flame stabilization conditions were compared. Consequently, a change of the material of the combustor significantly affected the flame stabilization compared to the effects of a scale-down design. A half-scale quartz combustor had a wide range of flame stabilization conditions. Surface temperatures and the composition of the emission gas were measured. At a higher flow rate, the combustor temperature increases and the light emission from the middle wall is enhanced to extend the flame stabilization conditions. The combustion efficiency and the composition of emitted gas were feasible. These results provide useful information for the design of small-scale combustors.

1. Introduction

With the recent development of small-scale mechanical systems, the importance of small energy sources has grown. The use of fossil fuels of greater energy density has been suggested as one of the strategies for such purposes [1–3]. As a practical method of using fossil fuel, micro-scale combustors have been investigated. These micro-combustors can be applied as a heat source, a photovoltaic source, a thrusting device, or a fuel reformer [1–12]. One of the key issues in the development of these types of small combustors is to overcome the spatial limits of gas combustion; namely the quenching limits. Concerned with the quenching limits, many previous studies have been conducted to promote the safety of combustors by protecting against flame flash-back [13,14].

It is known that the quenching distance is proportional to the flame thickness, that the flame thickness is inversely proportional to the burning velocity [15,16]. Hence, flame thickness should be reduced first to minimize the scale of the combustor. Several methods can be used for this, including an increase of the pressure to reduce the molecular distance, the use of special fuels or oxidants to induce a higher burning velocity, and the application of catalytic reactions to prevent termination of the chemical chain reaction [9–12]. However, these methods are not directly concerned with the design of the configuration of the combustor. They can be applied for most combustors after the best configuration of these combustors has been determined. Therefore, study of the most feasible configuration to overcome the ordinary quenching limits using a heat recirculation technique is of interest here.

For practical application of a micro-combustor, the following characteristics are necessary: conditions with greater flammability via heat recirculation, various combustion modes for various applications, an achievable emission gas composition, and reasonable combustion efficiency. Many trials have been conducted under the same purposes, and various small heat recirculation combustors have been developed [7–11]. The most representative of these is the ‘Swiss-roll’ combustor, which consists of a combustion space at the center and one or more couples of spiral channels for heat recirculation [7–9,17]. However, while these combustors are suitable for heat recirculation, they experience difficulties in

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Nomenclature

ϕ	equivalence ratio
V_m	mean velocity of mixture
T	Temperature
w	middle wall thickness
u	upstream channel gap
d	downstream channel gap
h	Combustion space height
BS	base-scale stainless steel combustor
HS	half-scale stainless steel combustor
HQ	half-scale quartz combustor

both experimental and analytical approaches due to their complex configuration and design parameters. The surface-to-volume ratio increases as the combustor scale decreases and the combustion phenomena depend significantly on the configuration of the combustor. Hence, estimating the effects of practical design parameters on the performance is essential for the development of a micro-combustor. Therefore, a flat-type heat-recirculative micro-combustor, as shown in Fig. 1a, is suggested as a basic configuration.

Investigations of flat-type or one-dimensional heat recirculation combustors in the form of theoretical and numerical studies have been continuously conducted [6,18–21]. However, additional studies are necessary to expand on the many practical issues that have been found in the development of micro-combustors. In the present study, following issues are investigated:

(1) Flame stabilization characteristics: The design parameters of base combustors are examined.
(2) Scale-down effects: The characteristics of scale-down combustors are examined.
(3) Material property effects: Scale-down stainless steel and quartz combustors are compared.
(4) The surface temperature and the gas composition are examined.

2. Experimental method

A mixture of CH_4 (99.999%) and compressed air from air cylinder (21% O_2, 79% N_2) was supplied by two mass flow controllers through a mixing chamber. An equivalence ratio ϕ and mean velocity V_m were used as experimental parameters. The mean velocity indicates the mixture flow rate at room temperature divided by the cross-sectional area of the upstream channel. Two types of materials were used to make combustors: stainless steel and quartz. The stainless steel combustors shown in Fig. 1b consist of many stainless plates. Hence, the middle wall thickness w, the upstream channel gap u, and the downstream channel gap d denoted in Fig. 1a are variable. The dashed line in Fig. 1b indicates the flow path of the mixture from the inlet to the outlet. The mixture passes through a narrow slot at the inlet to enhance the uniformity of the velocity. A quartz window with a thickness of 3 mm was installed on the upper side of the combustor for observation. A space larger than the channel scale, termed as a *combustion space*, exists at one end where an igniter is installed and the flow direction changes.

In this study, combustors with a channel width 20 mm and a channel length 150 mm are termed *base combustors*. Scale-down combustors of stainless steel and quartz were also fabricated. The length and width of these combustors were reduced to 50–60% of those values of the base combustor. Thus, the scale-down combustors are termed *half-scale combustors* for clarity. Direct photographs of the base combustor, the half-scale stainless steel combustor, and the half-scale quartz combustor are shown in Figs. 1c, 1d, and 1e, respectively. In the case of the quartz combustors shown in Fig. 1e, the upper and lower sides with different channel gaps are combined and an ignition wire was inserted through the downstream channel. Fig. 1f shows a schematic of the experimental setup.

Specific details of the combustors are given in Table 1. Each experimental case is denoted by two capital abbreviations of scale and materials followed by the three design parameters of the middle wall thickness w, the upstream channel gap u, and the downstream channel gap d. For example, 'BSw10u11d15' corresponds to a base-scale stainless steel combustor for which $w = 1.0$ mm, $u = 1.1$ mm, and $d = 1.5$ mm. Similarly, 'HQw10u11d30' corresponds to a half-scale quartz combustor for which $w = 1.0$ mm, $u = 1.1$ mm, and $d = 3.0$ mm. It is notable that the channel gaps in all conditions in this experiment are less than ordinary quenching distance of 2.5 mm of a methane/air mixture [14]. Therefore, heat recirculation must be used so that the flame will propagate into the channel.

In this study, all outer surfaces of combustors except the top side were insulated by using ceramic wool pad. Thickness of the wool pad did not affect the results when it was greater than 20 mm. Additionally, many K-type thermocouples of 0.5 mm diameter were installed in the longitudinal direction and at the exhaust port as shown in Fig. 1f. Temperature variations were recorded by a data logger (NI Compact DAQ) and the criterion of a steady state was defined when a temperature-time variation is less than 5 °C/min. The composition of the exhaust gas was measured using a flue gas analyzer (TESTO T330) of the repeatability of ±0.2% for O_2 and ±5% for CO in volume base. The gas-sampling flow rate was regulated by a flow-meter to be sufficiently smaller than that of an unburned mixture passing through the combustor.

3. Results and discussions

3.1. Flame stabilization modes

Direct photos of flames in combustors were depicted in Fig. 2. Three columns from the left side represent the cases of base combustors, half-scale stainless steel combustors, and half-scale quartz combustors, respectively. From the view point of application and control of combustors, flames in various experimental conditions were classified into four modes based on their characteristics. These modes were an *ordinary mode* (Fig. 2a), a *channel mode* (Fig. 2b), a *radiation mode* (Fig. 2c), and a *well-stirred reaction mode* (Fig. 2d). By comparing the experimental conditions of these four types of flame modes, combustion phenomena in micro-combustors can be better understood. Brief explanations of these four flame modes are given below.

3.1.1. Ordinary mode

Since the combustion space is slightly larger than the ordinary quenching distance, a flame near the stoichiometry can sustain in the combustion space without additional heat recirculation processes. Flame is located near the exit of the upstream channel and it moves closer to the exit of the upstream channel with a decrease of the flow rate and flashes back into the channel when the upstream channel gap is sufficiently large. In contrast, when the flow rate is excessively large, flame cannot be stabilized in the combustion space, and blow-out takes place.

3.1.2. Channel mode

Depending on the experimental conditions, flame can exist inside the upstream channel. A heat transfer typically occurs from