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Formation of ultra-lean comet-like flame in swirling hydrogen–air flow

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ABSTRACT

In this study, a hydrogen–air premixed flame in a partially tapered swirl burner in which a stable counterflow of unburned and burned gases is expected to be formed, was investigated. The experimental results indicate the formation of almost steady flames at equivalence ratios of as lean as 0.084, and the resulting ultra-lean flames in the swirling flow had a comet shape. Furthermore, the flame was numerically reproduced, and the mechanisms behind the phenomenon were identified by checking the balance among the chemical enthalpy through diffusion, heat flux by conduction, and transport of these parameters by convection. It was determined that the region around the tip of the flame head was almost dominated only by diffusion and heat conduction similar to a flame ball, but its formation mechanism was found to be essentially different from that of a flame ball because the comet-like flame can be numerically reproduced even without a radiative heat loss, in contrast to a flame ball.

1. Introduction

Hydrogen combustion currently attracts a significant amount of research attention because it is intrinsically free of CO_2 emissions. Recently, potentials for the industrial use of hydrogen have increased, and various methods are available to produce hydrogen [1]. Nevertheless, the characteristics of hydrogen combustion remain to have not been fully revealed, which can be an impediment for the utilization of hydrogen in applications such as gas-turbine combustors. Recently, industry demand to realize hydrogen combustion in gas-turbine systems has increased [2]. Considering such situation, the interaction between pure-hydrogen combustion and swirling flow has not been well studied; thus, a significant demand for the elucidation of pure-hydrogen combustion characteristics in a swirling flow arises.

For a long time, swirling flow has been utilized to stabilize the flame in high-velocity flows [3]. So, far, several types of swirler, e.g., axial and radial swirlers, have been developed, and almost all gas-turbine combustors have employed these swirlers to stabilize combustion. Adequate swirling flow forms a recirculation zone, which is believed to generate hot and radical-rich products to the reaction zone.

To understand the lean flame characteristics in a swirling flow for each fuel, the authors performed quasi-one-dimensional (1D) numerical calculations using the detailed kinetics of rotating-counterflow premixed twin flame (RCTF) of methane–or hydrogen–air based on a similar solution. As a result, we determined that an ultra-lean flame can be formed using both fuels when a backflow region of burned gas exists [4,6]. In RCTF, the flame position and flow configuration change with the rotation number, injection velocity, and equivalence ratio, and a backward flow region is formed when the rotation number is large. We note that under ultra-lean conditions, the flame surface is located within the backflow region of the burned gas. In such situation, the fuel preferentially diffuses toward the flame surface against convection, whereas the oxygen diffusion is overcome by the convective transport. This difference between the transport of fuel and that of oxygen increases the local equivalence ratio and flame temperature. We call this scenario as "net flux imbalance." For hydrogen–air ultra-lean flames, the maximum increase in the flame temperature from the adiabatic case was determined to reach approximately 600 K. This increase is caused by the combined effects of the net flux imbalance and preferential diffusion of hydrogen, which is one of the Lewis-number effects.

Note that, in this study, we define the term "ultra-lean" as a condition that is leaner than the generally known flammability limit of $\phi = 0.099$ [7], which was determined by the standardized 1D flame-propagating duct experiments. Recently, some

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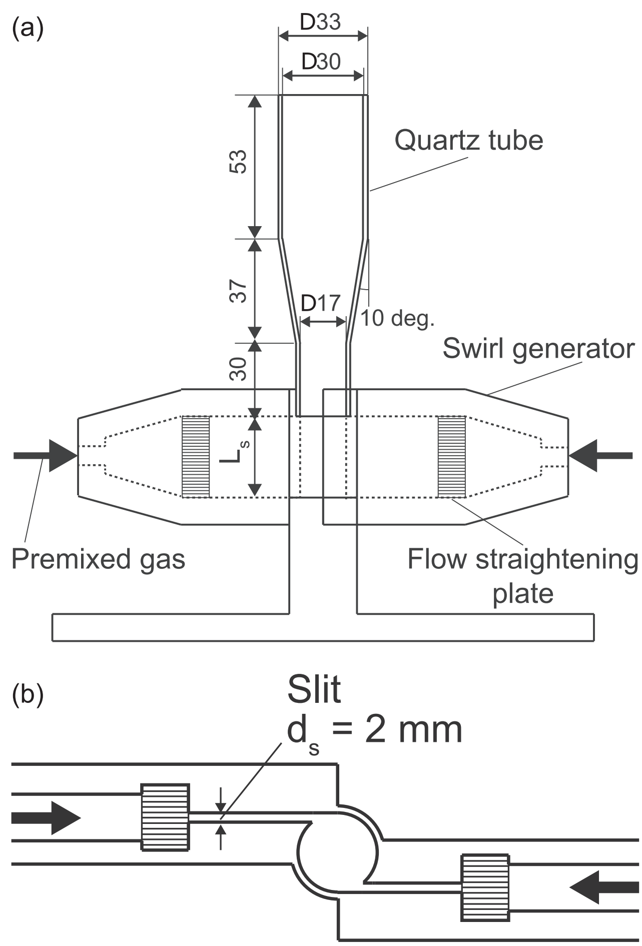

Fig. 1. Schematics of the experimental setup. (a) Whole configuration of the burner. (b) Cross section of the swirl generator.

studies have revealed that flames of certain configurations can sometimes exist under conditions considerably leaner than the flammability limit, i.e., equivalence ratio $\Phi = 0.082$ and 0.07 [8].

We desire to confirm that the above-mentioned phenomenon actually occurs in real life. However, RCTF is a hypothetical flame that cannot be experimentally formed because it is based on the assumption that the injection planes are infinitely large. Therefore, we decided to choose a more realistic flame as a target in which a similar phenomenon may occur. We, therefore, adopted a hydrogen–air premixed flame formed in a partially tapered tube that can be accompanied by a backflow region of burned gas and examined whether a very lean flame can exist. In the experimental process of examining the leanest extinction limit, we observed an unexpected combustion phenomenon, namely, comet-like flames. In this study, we try to both experimentally and numerically identify and investigate this newly observed combustion phenomenon.

2. Method

2.1. Burner configuration

Figure 1 shows a schematic of the experimental setup adopted in this study. The apparatus was composed of a swirl generator and a partially tapered quartz tube with a conical frustum section. The swirl flow was formed through two slits with width $d_s = 2$ mm, and their lengths L_s were varied from 10 to 40 mm, as mentioned in Section 2.3. The inner diameter of the swirl generator and the tube was 17 mm, and the length of the tapered section was 37 mm with an inclination angle of 10°.

In this study, lean extinction points in the map of equivalence ratio ϕ versus the total flow rate were measured for a hydrogen–air premixed flame. The existence or extinction of the flame was visually determined by monitoring the flame using an intensified charge-coupled device (ICCD) camera (Hamamatsu C7972-01 G), which is sensitive to wavelength ranges between 185 and 850 nm.

Mass-flow controllers were used to set the flow rates of the fuel and air. When the lean extinction points were measured, the fuel flow rate sufficiently and slowly decreased with the fixed-air flow rate until flame extinction was observed. Total volume flow rate Q, the mean injection velocity from each slit, and ϕ of the premixed gas gradually decreased during this operation. During the measurement, the flame was monitored by the ICCD camera, and the lean extinction point was defined as the instant when the flame disappeared from the monitor. We note that the condition under which a flame disappeared within 1 min after the changes in the flow rates was not counted as a flammable condition.

2.2. Computation of a swirling flame

2.2.1. Calculation domain and boundary conditions

Figure 2 shows the theoretical model and boundary conditions of a swirling flame. The origin of the cylindrical coordinate system is located at the center of the injector exit, and x and r denote the axial and radial distances, respectively. Variables u, v, w, T, and Y_k denote the axial velocity, radial velocity, circumferential velocity, temperature, and mass fraction of the kth species, respectively, whereas T_{S1} and T_{S2} denote the wall temperatures of the injector and outer tube, respectively. We assumed that the investigated phenomenon was completely axisymmetric. Note that all variables, including circumferential velocity w, are independent of angular coordinate θ.

Instead of the two slits in the experimental swirl generator, the premixed gas was injected with radial velocity $v = V$ and circumferential velocity $w = W$ around the entire circumference at the range of x that corresponded to the experimental swirl generator. The numerical total flow rates of the premixed gas were identical to those of the experiments. The temperature at the inlet was fixed at room temperature (300 K). The wall boundary of the burner was set to be adiabatic. In reality, the resulting gas temperature at the wall hardly differs between this adiabatic case and the fixed-temperature (300 K) case because the numerically obtained flames are so slim that their thermal influence does not reach the wall.

2.2.2. Equations and employed models

The governing equations for unsteady axisymmetric swirling reactive flow in cylindrical coordinates are expressed as follows, which are modified from a previous study [9]:

$$r\frac{\partial \rho}{\partial t} + \frac{\partial (r\rho u)}{\partial x} + \frac{\partial (r\rho v)}{\partial r} = 0, \quad (1)$$

$$\frac{\partial (r\rho u)}{\partial t} + \frac{\partial (r\rho uu)}{\partial x} + \frac{\partial (r\rho vu)}{\partial r} = -r\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\left\{\frac{4}{3}\mu r\frac{\partial u}{\partial x} - \frac{2}{3}\mu\frac{\partial (rv)}{\partial r}\right\} + \frac{\partial}{\partial r}\left\{\mu r\left(\frac{\partial u}{\partial r} + \frac{\partial v}{\partial x}\right)\right\} + r\rho g, \quad (2)$$

$$\frac{\partial (r\rho v)}{\partial t} + \frac{\partial (r\rho uv)}{\partial x} + \frac{\partial (r\rho vv)}{\partial r} - \rho w^2$$