Combustion and Flame 161 (2014) 1499–1506

Contents lists available at ScienceDirect

Combustion and Flame

journal homepage: www.elsevier.com/locate/combustflame

An assembled annular stepwise diverging tube for the measurement of laminar burning velocity and quenching distance

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ARTICLE INFO

Article history:
Received 5 September 2013
Received in revised form 26 October 2013
Accepted 19 November 2013
Available online 13 December 2013

Keywords:
Burning velocity
Quenching distance
Premixed flame
Diverging tube
Critical propagation velocity

ABSTRACT

Laminar burning velocities of premixed flames provide essential data in combustion studies. To facilitate an in situ monitoring in the field, a method using the annular diverging tube (ADT) and its improved version of the annular stepwise diverging tube (ASDT) were introduced in previous studies. Although the reliability and applicability of these methods has been verified, additional improvements are necessary for the field application. In this study, an assembled annular stepwise diverging tube (A-ASDT) was introduced. Each step-unit was fabricated separately to have higher dimensional precision and to selectively assemble suitable step-units. Thus, the burner configuration could be easily adjusted, and the experimental resolution could be controlled. Heat transfer through the burner was suppressed to extend the duration of the experiment. The characteristics of the critical flame-propagation-velocity (FPV) that are less affected by the channel gap scale were investigated in more detail. The critical FPVs were comparable to the laminar burning velocities for methane, propane, and DME. The quenching distances could be measured easily, and the quenching Peclet number was directly evaluated. In conclusion, in our knowledge, this A-ASDT may be one of the fastest, easiest, and approvable methods for the prediction of the laminar burning velocity and the quenching distance. Therefore, it can be adopted in the fuel-consuming field to monitor the characteristics of flammable mixtures.

1. Introduction

Laminar burning velocities and quenching distances of premixed flames provide essential data in combustion studies. Various experimental methods have been used [1–13] for the measurement of the laminar burning velocities; the flat flame method, the constant bomb method, the free propagation method, the opposed or impinging flow method, etc. Although some of these methods might provide more reliable values, they have been mostly conducted in laboratories and pose some difficulty when used in the engineering field. Various fuels and their mixtures are extensively consumed in the recent combustion field. Thus, a faster and easier scheme for the measurement of the laminar burning velocity is necessary.

Based on this motivation, an annular diverging tube (ADT) method [14] was introduced. In that study, a flame was formulated in the ADT that consisted of a quartz tube and a slightly tapered core column. The flame shapes and locations were monitored simultaneously with the decrease in flow rates. It was found that the critical flow velocity when the flame shape was least inclined was comparable with the laminar burning velocity. To simplify the measuring process, an annular stepwise diverging tube (ASDT) was introduced [15]. By using a stepwise core instead of the slightly tapered core, consecutive flow divergences could be introduced at every step. Thus, flames could be stabilized near a step with the flat shapes in the azimuthal direction. Thus, the flame-propagation-velocity (FPV) could be estimated by just reading the flame location at the fixed flow rates, namely through a static method.

The ADT or ASDT methods were based on the numerical and experimental results regarding the propagation characteristics of premixed flames in cold narrow channels or tubes [16–20]. Numerical studies [16,17] have reported that a stationary flame has a critical FPV that is less affected by the scale of the channel gap or tube diameter, as shown in Fig. 1 [15]. The existence of the critical FPV was observed in some experimental studies [18–20], and it was shown that the critical FPV was similar to the laminar burning velocity, S_L^0 [14,15]. The critical FPV was thought to be maintained by the competition between the negative effect of heat loss from the flame to the wall and the positive effect of flow redirection near the flame front determined by the flame shapes.

Nevertheless, there have been some obstacles the ASDT method [14,15] performing better. First, finer step-scales are necessary to

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http://dx.doi.org/10.1016/j.combustflame.2013.11.020

Nomenclature

d	core diameter
D	tube diameter
L	core length
ΔL	step length scale
Q	volumetric flow rate
S_L^0	laminar burning velocity
T	temperature
V	average flow velocity
w	channel gap scale
Δw	step scale of channel gap
x	stream wise distance
ϕ	equivalence ratio
Acronym	
ADT	annular diverging tube
ASDT	annular stepwise diverging tube
A-ASDT	assembled-ASDT
FPV	flame propagation velocity
Subscript	
crit	at critical propagation
f	at flame
n	at *n*-step
q	at quenching

get more precise results. However, regulating manufacturing precision through dozens of the whole steps is a formidable task. Second, the burner should be maintained as a cold state, thus the heat transfer through the burner needs to be suppressed more to improve the duration of the measurement. Third, the measuring resolution and reliability needs to be adjusted more easily since the necessary experimental resolution and the measuring range may differ in the various applications.

In this study, therefore, a new burner configuration of an assembled annular stepwise diverging tube (A-ASDT) is introduced. To achieve a more precise dimension, every step-unit is fabricated separately. After that, suitable step-units are chosen depending on experimental ranges and necessary resolutions. Then, the selected step-units are assembled, and a narrow cavity gap is arranged between neighboring step-units by inserting an additional metal O-ring. Using the A-ASDT, the suppression of the thermal conduction is first examined, and the controllability of the experimental resolution is investigated. In addition, the existence of the critical FPV is examined in more detail for methane, propane, and DME. Based on the characteristics of the critical FPVs, an easier experimental method for the prediction of the laminar burning velocity will be suggested. Finally, the quenching distances are measured and the quenching Peclet number is discussed. This study will help develop an in situ monitoring method for the burning velocity and quenching distance in the fuel-consuming field and help understand flame characteristics in small-scale combustion spaces.

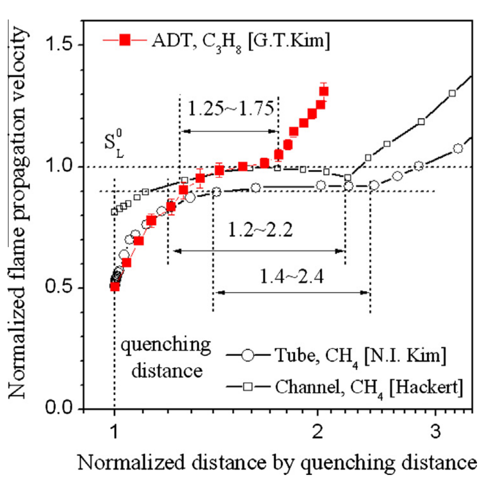

Fig. 1. Existence of critical propagation velocity in narrow tubes or channels [15].

2. Experimental methods

A schematic of the experimental setup is shown in Fig. 2a. Dehumidified air (<1% humidity) was mixed with fuels; methane (>99.995%), propane (>99.95%), and DME (>99.9%). Their volumetric flow rates were calibrated with gas flow-meters (Shnagawa, W-NK 0.5A, DC-2C, Japan), and they were controlled with mass flow controllers (<2% error). Experiment was conducted with the gas temperature of 293–299 K under the atmospheric pressure. In some cases, the mixture was flown out through a by-pass line equipped with a rotameter (<2% error, ALLBORG, USA), with the purpose of controlling the flow rate keeping the equivalence ratios. The burner consists of an outer quartz tube and a stepwise core. The stepwise core was assembled with many step-units that were fabricated separately, as shown in Fig. 2b. The dimensional precision was significantly improved; i.e., the average deviation in the radii of steps was 21 μm in the previous study [15] and was

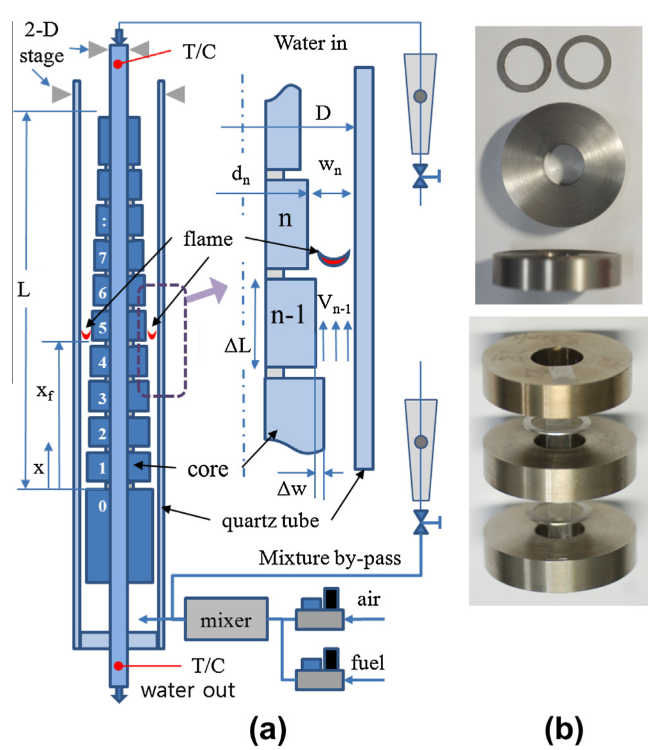

Fig. 2. Experimental apparatus: (a) experimental setup and (b) photo of step-units and stainless steel O-rings.