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On the instability of a modified cup-burner flame in the infrared spectral region☆

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Summary This study describes the modification of a standardised cup-burner apparatus. The replacement of the original glass chimney is performed by shielding a nitrogen co-flow enabled measurement at a wavelength of 3.9 μm. This modification, together with a special arrangement of the measuring system (spectral filtering, data acquisition and post-processing), permitted the observation of various types of hydrodynamic instabilities, including transition states. The advantages of our arrangement are demonstrated with an ethylene non-premixed flame with high sooting tendency. Two known modes of hydrodynamic instability (varicose and sinuous) that occur in buoyant flames were studied and described quantitatively. Based on the intensity of the infrared emissions, we identified and qualitatively described the modes of periodic hydrodynamic instability that are accompanied by flame tip opening, which has not been observed for this type of flame.

Introduction

The authors of review (Steinhaus et al., 2007) clearly showed that despite the enormous body of work on large-scale pool fires there is a critical need for more well instrumented experimental studies. Investigation of the hydrocarbon flames in the laboratory scale is one of the keys for understanding to the hydrodynamics and heat transfer processes involved in real industrial fires.

In order to analyse the instability modes of laminar non-premixed sooting flame we chosen a standardised cup-burner apparatus. It is frequently used as testing equipment to determine the minimal concentrations of gaseous

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Nomenclature

SD_{max}	maximum standard deviation (a.u.)
I_{max}	maximum soot radiation intensity (a.u.)
HAB	height above burner (m)
Ri_0	initial Richardson numbers $\left(= Dg/v_0^2\right)$, (−)
D	diameter of fuel nozzle (m)
g	gravitational acceleration (m s^{-2})
v_0	initial velocity of fuel (m s^{-1})

fire suppression agents (Senecal, 2005) or to investigate flame extinguishment processes (Katta et al., 2004, 2006; Takahashi et al., 2007; Linteris et al., 2007; Bitala et al., 2013). In addition to methods such as velocimetry and computational fluid dynamics (CFD), the flame of a cup-burner has been studied using narrow-band emission measurements in the visible region (Takahashi et al., 2007). These measurements mainly yielded a spatially and temporally resolved characterisation of a methane (CH_4) flame with a relatively low sooting tendency.

The infrared (IR) spectral region can be useful for the diagnosis of highly sooting flames (e.g., Docquier and Candel, 2002). Currently, broad-band measurements have been used for this purpose (Hayasaka, 1996; Planas-Cuchi et al., 2003).

This work was performed to investigate the properties of a modified cup-burner system for monitoring spatially and temporally resolved radiative properties of an ethylene (C_2H_4) flame in a narrow-band for a wavelength of approximately 3.9 μm. This wavelength was selected based on the intention to monitor the IR emissions of soot particles and to simultaneously eliminate the irradiation of gas phase species present in the flame. In addition, the special arrangement of the measuring system and the data evaluation procedure were enabled to observe and describe various types of the hydrodynamic instabilities in the flame.

To measure the cup-burner flame in this spectral region, the original chimney was replaced by a shield co-flow system.

Experimental

Modification of the burner

The design of our apparatus was fundamentally based on standards ISO 14520 (14520-1) and NFPA 2001. The main modifications were as follows (Fig. 1):

(a) The replacement of the original glass chimney by an outer co-flow shroud.
(b) The modification of the diffuser.
(c) The modification of the fuel nozzle.

Ad (a) The outer co-flow was used to ensure the transmissivity of radiation in the middle IR region. Nitrogen was used as the shielding gas and was fed into the co-flow shroud through three horizontal inlets at angles of 120°.

Ad (b) In contrast to the system described in the standard, we added two inlets to supply the oxidiser (air), and the final arrangement had a total of three inlets at angles of 120°.

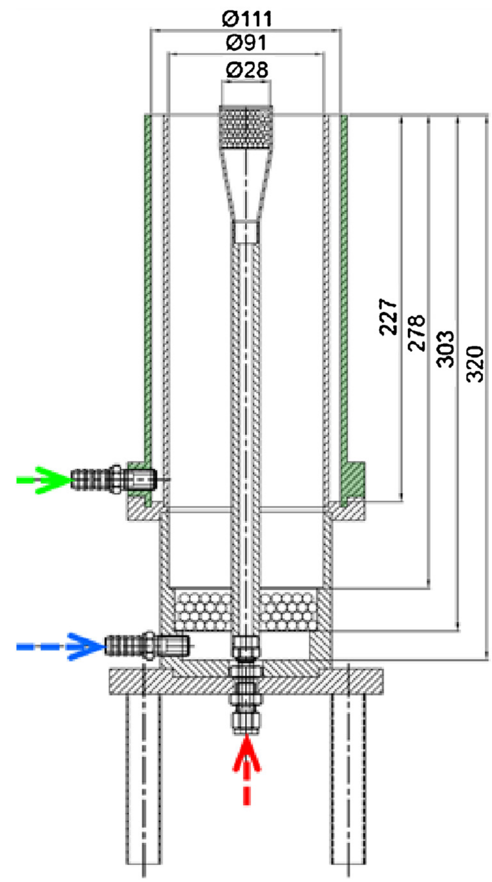

Figure 1 Simplified scheme (cross-section) of the modified cup-burner apparatus. The green highlighting corresponds to the additional nitrogen co-flow shroud. The red arrow designs a fuel inlet, the blue arrow designs oxidiser inlet into the diffuser, and the green arrow shows the nitrogen inlet.

This arrangement was used to increase the homogeneity of the oxidiser flow to ensure the axial symmetry of the flame.

Ad (c) The fuel nozzle cup was filled with a layer of 3 mm glass beads and was covered with two stainless steel wire meshes. This modification was similar to the work of Katta et al. (2004, 2006), for obtaining a uniform inlet velocity profile of the gaseous fuel.

Experimental setup

The experimental arrangement is depicted in Fig. 2. The flow rates of the gaseous fuel (C_2H_4 − 99.9% Linde Gas), oxidiser (compressed air, SIAD) and co-flow nitrogen (99.999%, Messer) were controlled by the Aalborg-type rotameters.

The spatially resolved emissions were monitored by an IR camera (Electrophysics PV320L2ZE) that has a BST pyroelectric focal plane array with a 240 × 320 pixels detector and is covered with a ZnSe window. The measurement was performed using a 35 mm lens system with germanium lens and integrated a manually adjustable iris diaphragm. The spectral band-pass filter (Spectrogon BBP type) with a transmissivity of less than 5% at wavelengths outside the 3.75—4.02 μm range was placed between the camera lens and the detector window.