

Diffusive Thermal Instabilities of C_4H_{10} - C_3H_8 /Air Laminar Premixed Flames

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Abstract

Preferential heat and mass transfer induces diffusive thermal instabilities in premixed laminar flames. Such instabilities in hydrocarbon flames are characterized by cellular structure and a tendency to promote flame extinction. We investigate the properties of such instabilities in C_4H_{10} - C_3H_8 /air flames. The adiabatic burning velocity of the laminar premixed flame was measured at different equivalence ratios while exhibiting cellular instabilities. Direct photographs have been captured to qualitatively assess the effect of burner plate temperature on the cellular structure of the flame. The present study preliminarily suggests a normal logarithmic correlation to predict the adiabatic burning velocity of diffusive thermal instabilities in laminar premixed C_4H_{10} - C_3H_8 /air flames.

Keywords

diffusive instability, flame dynamics, premixed gaseous flame, hybrid fuel combustion

1. Introduction

One fundamental characteristic of premixed laminar flames is the nature of the reaction zone. It forms a thin region on the interface between burnt and unburnt mixtures [1]. A portion of the burnt gases propagates inside the reactants heating the mixture to reach its flammability limit, in order to sustain the flame. On the other hand, non-premixed flames maintains the combustion zone within the fuel and the oxidizer interface. In this region, a sufficient amount of fuel and oxidizer are mixed to sustain the flame. Hence, it is clear that the flow conditions of mixture and fuel are very crucial in sustaining both premixed and non-premixed flames, respectively. Thus, premixed flame can be said to be stable within certain flow limits. There are two types of stability limits with laminar flame propagation [2]. The

first stability type of the mixture is found to support the flame propagation. It includes flammability limits and the quenching distances. The other type is concerned with flow conditions which involves the phenomena of flashback, blow off and the anchoring of flames on burners [3-5].

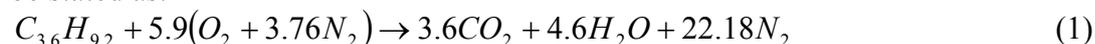
It is well known, that subsonic, premixed and non-premixed, flames encounter diffusive thermal instabilities due to preferential diffusion of mass and heat [6-9]. These instabilities, which occur at low Lewis number, might lead to cellular flame structures, only if the mixture flow was purely laminar. The low Le numbers reflects lean mixtures of light fuels, or rich mixtures of heavier fuels. In fact, such instabilities, in conjunction with the flame stretch effect, are somehow vital when it comes to flame extinction [10]. Hence, these instabilities represent an important concern when it comes to designing efficient and reliable combustion systems.

A major factor to characterize the premixed flame instabilities is the adiabatic burning velocity. Two methods are well known for measuring this velocity; the counter flow method [11] and the heat flux method [12]. Flame stretch effects impose some sort of extrapolations in the counter flow method. While in the heat flux method, such extrapolations are not required since the heat required for flame stabilization is directly measured. In 1954 Botha and Spalding studied the heat required for flame stabilization by measuring the temperature rise of cooling water through a burner [13]. Several enhancements to the method were added in the following years. Measurement of the heat required for flame stabilization through cooling water was replaced by measuring the surface temperature of a thin perforated plate as in [14]. The thickness to radius ratio of such perforated plate was set at a very small value to neglect the temperature variation across the plate thickness. In such case, the flame stabilization quality can be captured by measuring the surface temperature of the plate at several locations. Plate temperature is an indication of the heat transferred from the flame to the plate in this case. By heating the perforated plate, such heat loss is compensated, and the flame is deemed to be adiabatic.

In the present work, the heat flux method is used to determine adiabatic burning velocities at which C_4H_{10} - C_3H_8 premixed flames exhibit diffusive thermal instabilities. A mathematical formulation of the problem parameters are given in the second section followed by a detailed description of the experimental setup. The experimental results and the corresponding statistical analysis are comprehensively discussed before the conclusion.

2. Reaction and flame formulation

In this study, the fuel used is a mixture of 40% propane (C_3H_8) and 60% butane (C_4H_{10}) (commercially known as LPG) and the oxidizer is ambient air. Through a simple molar analysis of the combustion of such mixture with air, the stoichiometric reaction equation can be stated as:



where the stoichiometric air/fuel ratio equals 15.42

For the actual combustion, the equivalent ratio is a measurement of the air-fuel mixture relative to stoichiometric conditions, which defines as

$$\phi = (A/F)_{stoic} / (A/F)_{actual} \quad (2)$$

where

$$(A/F)_{actual} = \frac{\text{Air mass flowrate, } m_{oxidizer} \text{ (kg/s)}}{\text{Fuel mass flowrate, } m_{fuel} \text{ (kg/s)}} \quad (3)$$

when:

$\phi < 1$: Lean combustion, oxygen remains in the products

$\phi = 1$: Stoichiometric combustion

$\phi > 1$: Rich combustion, CO and fuel remains in the products

The adiabatic burning velocity,

$$S_L = \frac{Q_{Fuel} + Q_{air}}{A_b} \quad (4)$$

3. Experimental Setup

The experimental setup used in the present work is based on the work of Bosschaart and Goeij [16]. However, the burner plate was redesigned in order to compensate the difference in properties between LPG and methane. The experimental configuration is detailed in figure 1.

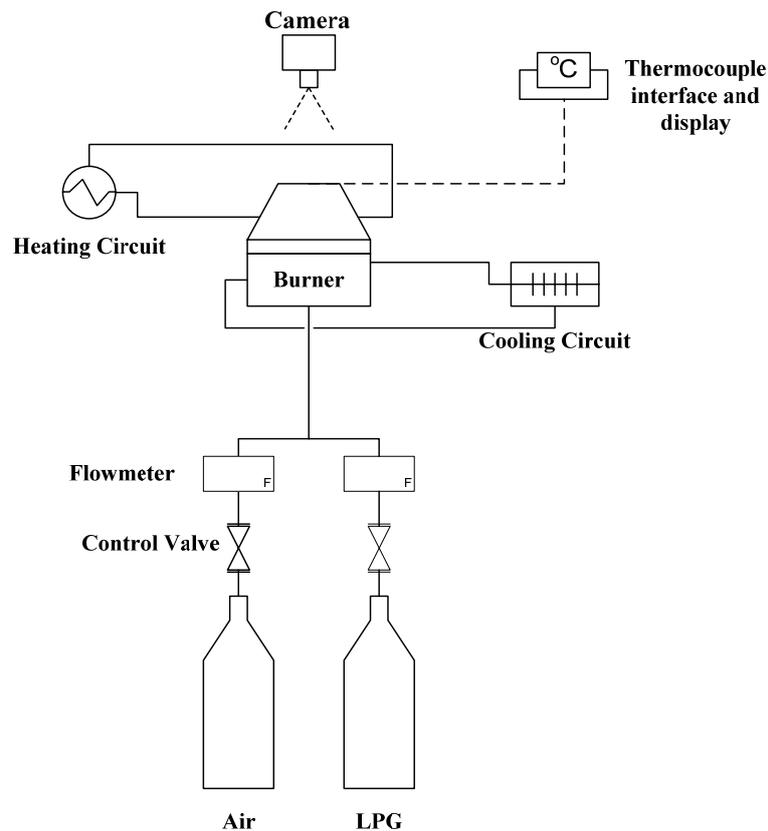


Figure 1. Experimental setup for the heat flux method

The burner assembly contained three main components; a plenum chamber, a burner head and a perforated plate. A schematic of the burner assembly is shown in figure 2-a. The fuel and air mixture was supplied to the burner head at constant temperature. This was achieved by maintaining the plenum chamber temperature constant through an automatic cooling circuit, as in figure 2-b. By maintaining the LPG-air mixture supply at constant temperature, the value of added heat through the heated burner plate can be accurately determined.

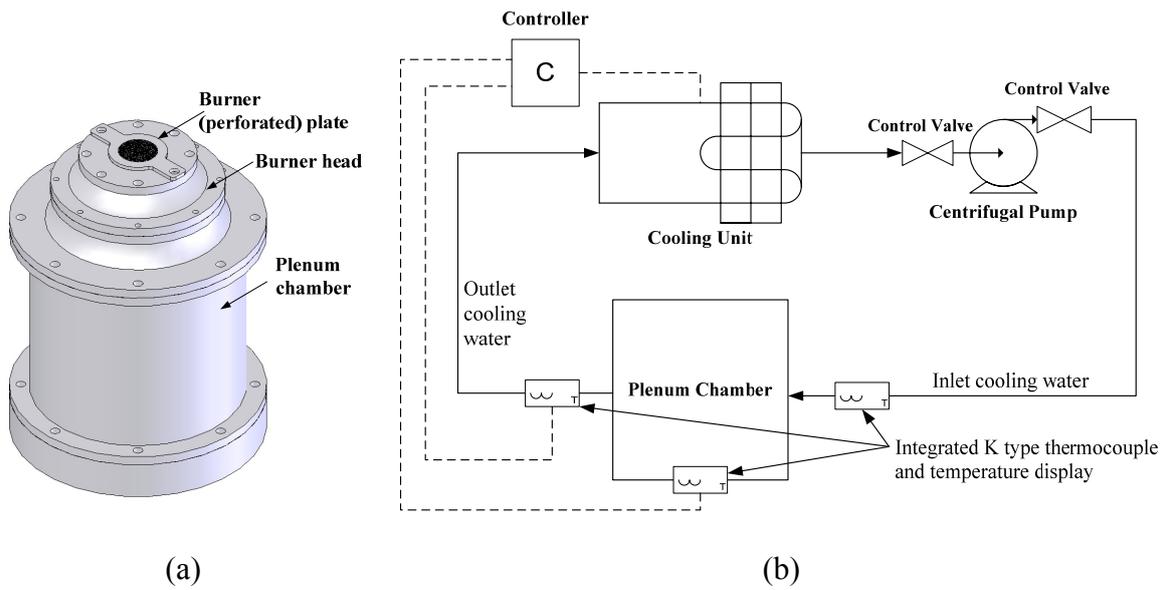


Figure 2. (a) Burner assembly (b) The plenum chamber water-cooling circuit

The aluminum burner head was designed with an internal passage geometry that ensures uniform flow for the LPG-air mixture. The upper part of the burner head was heated through an automatic heating circuit, as explained in figure 3. Such added heat, in this stage, is supplied in order to compensate the heat transferred from the flame to the burner plate, hence, ensuring adiabatic flame propagation. The burner perforated plate was made from brass and it had a pattern of holes with pitch to diameter ratio of 1.4. The perforated plate, as illustrated in figure 4, was compactly attached to the burner head in order to utilize the thermal contact resistance in providing more uniform temperature distribution across the plate surface.

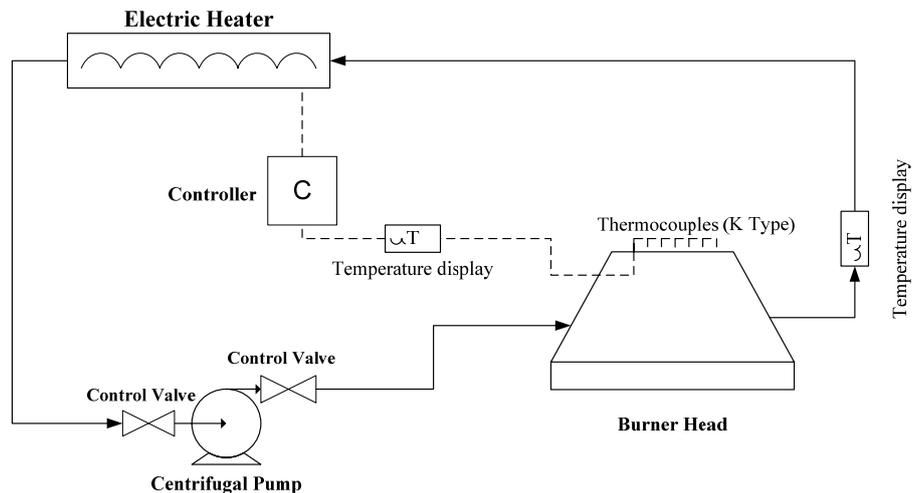


Figure 3. Water-heating circuit for the burner

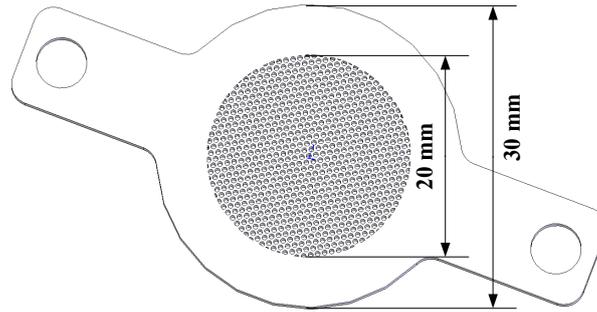


Figure 4. Perforated burner plate

The following section presents experimental results that cover a range of equivalence ratios from 0.4 to 1.8 at constant plate temperatures of 318 K and 323 K. LPG fuel and air were mixed at a Y shaped junction before the plenum chamber. The cooling circuit was operated such that the plenum chamber temperature was maintained for all experiments at 293 K, which is the same temperature of the unburnt mixture. All experiments were conducted in a dark enclosure in order to enhance the photographs quality.

4. Results and Discussion

At burner plate temperature of 318 K, the cellular instabilities are exhibited over a wide range of equivalence ratios, mostly in the lean side, as in figure 5. The upper and lower limits of adiabatic burning velocity for cellular instability are 40.1 cm/s and 17 cm/s respectively. It is obvious that the flame is more susceptible to cellular instabilities at low equivalence ratios.

A logarithmic regression model [17] has been used with the data in figure 5 to devise a correlation for the prediction of adiabatic burning velocity LPG/air flames exhibiting cellular instability as a function of the equivalence ratio. The proposed correlation has shown to have prediction quality of approximately 65% when it was used to predict adiabatic burning velocity at different equivalence ratios and burner plate temperature. In the proposed correlation the burner plate temperature is not included as the flame is assumed to be at a fully adiabatic condition. A comparison between the predicted and experimentally measured data is detailed in figure 6.

The proposed correlation is:

$$S_L = 18.849 + 22.091 \times e^{-0.5 \left[\frac{\ln \frac{\phi}{0.9104}}{0.289} \right]^2} \quad (5)$$

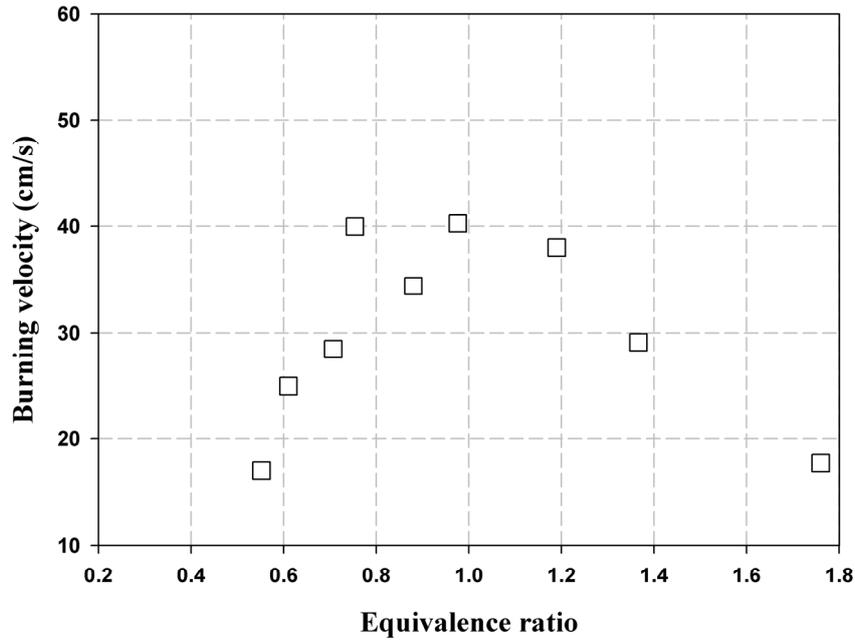


Figure 5. Adiabatic burning velocity of cellular LP/air flames at burner plate temperature of 318 K

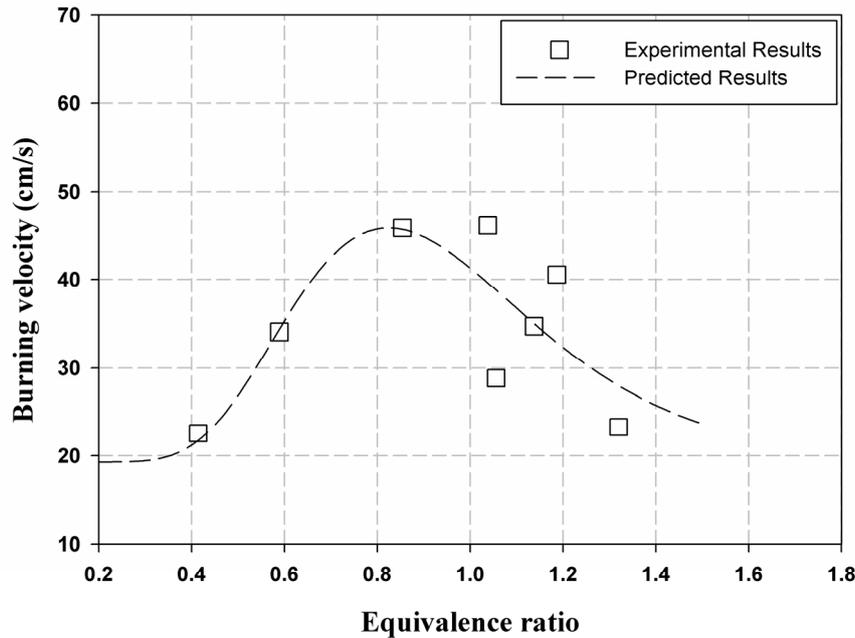


Figure 6. A comparison between experimentally measured and predicted adiabatic burning velocity of cellular flame at burner plate temperature of 323 K

In addition, at the burner plate temperature of 323 K, cellular instabilities was found to occur more at rich equivalence ratios. The maximum and minimum adiabatic burning velocity for cellular instable flames in this case are 46.1 cm/s and 22.5 cm/s.

The structure of cellular instabilities is dramatically affected by the equivalence ratio, as indicated by the photographs in figures 7 and 8. At burner plate temperature of 318 K, the cellular flame structure was found to have, generally, more defined and well separated cells. Such separation in the cellular structure, though, tends to diminish at higher equivalence ratios as in figure 7. In fact, the boundaries between cells are thin regions of unburnt mixture formed

due to the diffusive thermal instabilities. When the burner plate temperature was increased to 323 K, the cellular structure changed as observed in figure 8. Instead of the "multiple" cell structure found at the lean equivalence ratio in figure 7, the cellular structure was found to have two large cells at lean equivalence ratio. The two cells were observed to be well separated as well. On the other hand, at rich equivalence ratios, the cellular structure began to lose its unique shape; the unburnt mixture boundaries between cells have almost disappeared.

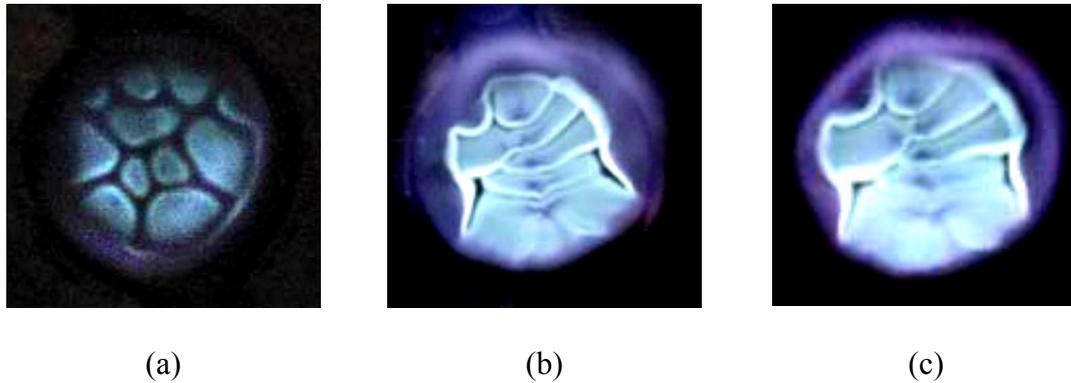


Figure 7. Cellular instabilities at 318 K (a) $\phi = 0.707$ (b) $\phi = 0.976$ (c) $\phi = 1.336$

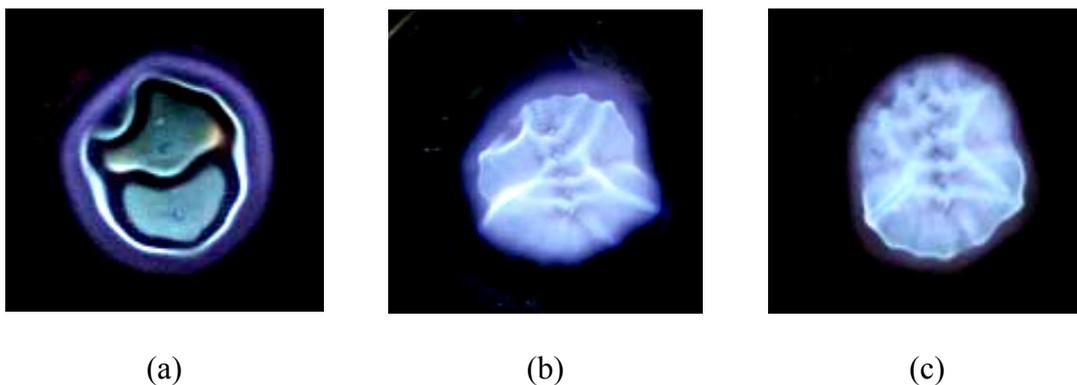


Figure 8. Cellular instabilities at 323 K (a) $\phi = 0.854$ (b) $\phi = 1.038$ (c) $\phi = 1.187$

5. Conclusions

The diffusive thermal instabilities of LPG/air laminar premixed flame have been experimentally studied at different equivalence ratios and burner plate temperature. The adiabatic burning velocity of the flame was reported during the cellular instability condition. The cellular instabilities of the flame have been qualitatively and quantitatively analyzed. The results suggest that the adiabatic burning velocity of cellular instabilities is subjected to a normal logarithmic relationship with respective values of equivalence ratio. In addition to equivalence ratio, burner plate temperature was evidently found to have radical effect on the structural quality of cellular instabilities. The present study recommends that intensive future research on instability of hydrocarbon mixture premixed flames should be carried out.

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Nomenclature

ϕ	Equivalence ratio (dimensionless)
A/F	Air to fuel ratio (dimensionless)
S_L	Adiabatic burning velocity (cm/s)
Q_{Fuel}	Volumetric fuel flow rate (cm ³ /s)
Q_{Air}	Volumetric air flow rate (cm ³ /s)
A_b	Effective surface area of the burner plate (cm ² /s)