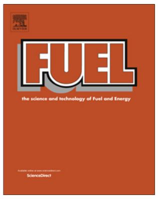
Fuel 136 (2014) 69–78

Contents lists available at ScienceDirect

Fuel

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



Effects of CO_2 addition on flame extinction in interacting H_2–air and CO–air premixed flames

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HIGHLIGHTS

- Chemical effects of added CO_2 in flame extinction.
- Flame stability maps with 0%, 10%, and 20% CO_2 additions.
- Effects of CO_2 addition in flammable islands and lean-extinction-boundary-opening.

ARTICLE INFO

Article history:
Received 10 November 2013
Received in revised form 9 May 2014
Accepted 5 July 2014
Available online 27 July 2014

Keywords:
Artificial species
Chemical effect
Downstream interaction
Extinction boundary
Strain rate

ABSTRACT

The effects of CO_2 addition on the downstream interactions of H_2–air and CO–air premixed flames were investigated. Flame stability diagrams mapping the extinction limits for various fuel concentrations as functions of the strain rate were developed for the downstream interactions between H_2–air and CO–air premixed flames with 0–20% CO_2 addition. Of particular concern was the impact of the chemical reactions of the additional CO_2 on the flame extinction characteristics. The results showed that CO_2 addition suppressed the flammable regions appreciably and decreased the critical strain rate, opening up the lean extinction boundary. For highly stretched interacting flames, two flammable island regions on the maps were combined into one when 10% or 20% CO_2 was added to either the H_2–air or CO–air premixed mixtures. The chemical reactions of the additional CO_2 were significant, especially for high strain rate flames, while the effect of the radiative heat loss of the additional CO_2 was minor, even for low strain rate flames. Such chemical reactions were determined by competition between the reaction steps for the consumption and production of HCO and the reverse reaction of $CO + OH = CO_2 + H$ with the reaction step of $H + O_2 \rightarrow O + OH$, an indicator of the overall reaction rate for the H atoms. This resulted in a weakened interacting flame. Such chemical reactions of the additional CO_2 were examined in detail to describe the flame characteristics.

1. Introduction

Public concern over global climate change has focused on man-made emissions of greenhouse gases, and in particular, the amount of carbon dioxide released during the combustion of fossil fuels. Thus, a sudden increase in energy demand will present a serious dilemma unless a new technology to replace existing fossil fuels is developed. Presently, it is difficult to restrict the utilization of existing fossil fuels. In this situation, synthetic gas obtained from the gasification of coal, biomass, and solid or liquid fuels is an attractive fuel, particularly for combined integrated gasification cycle systems. Syngas fuels are typically composed primarily of H_2 and CO, and may contain N_2, CO_2, H_2O, CH_4, and other higher-order hydrocarbons [1]. The composition of syngas obtained from different coal gasification plants can be summarized as 30–60% H_2–CO by volume with different H_2/CO ratios, with the rest being primarily N_2, CO_2, and moisture [2]. There is considerable variation in the composition of syngas, depending upon the various fuel sources and processing techniques. This variation is another

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http://dx.doi.org/10.1016/j.fuel.2014.07.009
0016-2361/

challenge in designing H_2/CO syngas combustors since these substantial variations in composition and heating values are problematic when designing an appropriate burner. The resulting variability in combustor performance and pollutant emissions requires further study of the fundamental combustion properties of these mixtures. Considerable research effort has been devoted to understanding the fundamental flame characteristics [3–9] and the reaction mechanisms [10,11] of syngas. Several fundamental issues with syngas diffusion flames have been addressed, such as the effects of additional CO_2 [3], preferential diffusion [12], and Lewis number [13].

Unless a well-refined gasification process is used to produce syngas, the inclusion of appreciable amounts of diluents (N_2, CO_2, and H_2O) cannot be avoided. This means that the direct use of syngas fuels must be confined to several specific combustion technologies, such as oxyfuel and mild combustion, because of the low calorific values of H_2 and CO flames, the stability problem of CO flames, and the excessive amount of diluents (CO_2, H_2O, and N_2). A more pertinent way to use syngas fuels is to directly blend them with hydrocarbons and/or to use syngas mixtures as a co-firing fuel. This has merit for alternative retrofit concepts since minimal modifications are required to convert existing industrial burners and obtain reduced CO_2 emissions. However, such flame configurations can raise issues regarding the downstream interactions between two flames established using different types of fuel. The downstream interactions between premixed flames using the same type of hydrocarbon fuel have been well described by the Lewis number in several comprehensive extended studies [14–17]. However, some anomalous aspects of the interactions of flames using different types of fuel [18–20] and even those using the same type of H_2/CO syngas fuels [21,22] cannot be explained by the Lewis number; instead, the chemical interaction (such as radical-sharing) and effects of flame stretching and preferential diffusion must be considered. Recently, drastic phenomena have been observed in the chemical interactions between H_2–air and CO–air premixed flames with extremely long and short chemical time scales [23]. These results showed that even a small amount of H_2 could modify the reaction route because the CO oxidation steps involving the hydroxyl radical (*i.e.*, $CO + OH = CO_2 + H$) proceeded more rapidly. This opened up the lean extinction boundary. Furthermore, highly stretched partially premixed flames survived in such a way that extremely rich H_2–air and lean CO–air premixed flames could act as parasites to the diffusion flame.

An appreciable amount of CO_2 is generally contained in syngas mixtures, depending on the gasification process. CO_2 has a large heat capacity and a high radiative heat absorption coefficient. Additionally, the presence of CO_2 in the flame zone can modify the reaction routes via the reverse reaction of $CO + OH = CO_2 + H$, thereby affecting the flame characteristics. However, the role of additional CO_2 in the interactions between H_2–air and CO–air premixed flames has not yet been addressed. Therefore, the downstream interactions between H_2/CO_2–air and CO/CO_2–air premixed flames were investigated in the present study. Flame stability mapping was carried out for different concentrations of H_2 and CO as functions of the global strain rate. The thermal, chemical, and radiative effects of the additional CO_2 on the flame extinction were then evaluated for a counterflow configuration.

2. Numerical strategies

The downstream interactions between premixed H_2/CO_2–air and CO/CO_2–air flames were investigated using the counterflow configuration shown in Fig. 1. A one-dimensional mathematical description of the interactions around the stagnation point based on a similarity variable is available. The model used in this study was developed by Kee et al. [24] and subsequently extended by Lutz et al. [25]. The details of the governing equations for the transport of mass, momentum, chemical species, and energy, as well as the solution techniques can be found in these two references. The global strain rate is defined as follows:

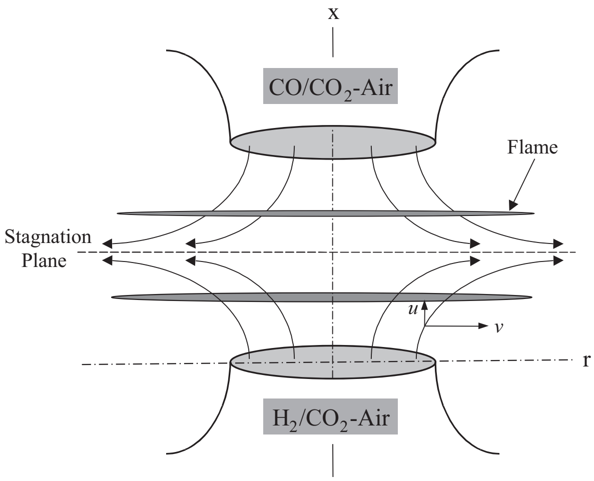

Fig. 1. Schematic diagram of the interacting counterflow premixed flame configuration.

$$a_g = \frac{V_U + V_L}{2L} \tag{1}$$

where V and L are the nozzle exit velocity and the nozzle gap, respectively, and the subscripts U and L refer to the upper and lower nozzle ducts, respectively. The burner gap was fixed at 15 mm. The fuel concentration was expressed as a volume fraction, as follows:

$$\Omega_i = \frac{V_i}{V_i + V_{CO_2} + V_{air}} \quad \text{where } i = H_2,\ CO.$$

Here V_i denotes the volume of i species. The nozzle exit velocities were used, so that the stagnation plane moved as the mixture compositions varies. However, the results was not influenced by with the same velocity boundary conditions because the reaction zone thickness was always smaller than the distance between two burners at $a_g \geqslant 30\ s^{-1}$. Radiative heat transfer can be significant in low-strain-rate flames, so that the flame thickness, and thereby the flame volume, are related to the inverse of $\sqrt{a_g}$. Because of this, radiation was included in the calculations. The main contribution to the radiative heat loss is from H_2O, CO, and CO_2, and the radiative heat flux with the optically thin approximation [26] can be expressed as

$$\dot{q}_r = -4\sigma K_p (T^4 - T_\infty^4), \tag{2}$$

where

$$K_p = \sum_{i=1}^{3} P_i K_i, \quad i = CO_2,\ H_2O,\ CO.$$

Here σ is the Stefan–Boltzmann constant, T and T_∞ are the local and ambient temperatures, respectively, and K_p is the Planck mean absorption coefficient. P_i and K_i are the partial pressure and the Planck mean absorption coefficient of a given species i, respectively. The mean Planck absorption coefficient can be approximated by a polynomial function of temperature. For CO_2 diluted flames, the flammability or extinction limit can be markedly affected by radiation re-absorption [27]. In reality, a narrowband model can predict the extinction limit precisely and make a flame more sustainable to extinction. However, as shall be shown later in Fig. 2c, when