

# Effects of Radiation Reabsorption on Flame Propagation and Flammability Limits in CO<sub>2</sub> Diluted Flames

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## Introduction

Thermal radiation is an important, often dominant, heat transfer mechanism in many combustion systems such as combustion in microgravity, ultra lean burning, sooting flames, and fire spreading (Spalding 1957, Turns and Myhr 1991, Guo et al. 1997). Recently, with the recent development of high pressure combustor for high energy efficiency and low NO<sub>x</sub> and soot emission technology, a large amount of CO<sub>2</sub> is recycled to the unburned mixture. CO<sub>2</sub> is a strong radiation emitter in flames and has been considered as one of the most effective fire suppressants for manned space flights. As such, the study of radiation dominated combustion, particularly for premixed combustion with CO<sub>2</sub> addition, has attracted a great attention (Ju et al. 1998).

Joulin and Deshaies (1986) analyzed the effect of radiation absorption by using a particle laden planar flame. They showed that flame speed increases exponentially with the increase of Boltzmann number and that there is no flammability limit when radiation absorption is considered. But this result is not experimentally validated. The effect of gray gas radiation absorption on the flammability limit was also investigated by Lozinski et al. (1994) in the study of flame ball and in the study of NO<sub>x</sub> formation in stretched counterflow nonpremixed flames by Vranos and Hall (1993). By using statistical narrow band (SNB) model in CO<sub>2</sub> diluted planar propagating flames, Ju et al. (1998) found that radiation absorption led to higher flame temperature and burning velocity than the adiabatic flame. The studies of radiation effects on the self-extinction-flame and flame ball were also conducted (Abbud-Madrid and Ronney 1993, Abid et al. 1999, and Wu et al. 1999). The results showed that the prediction without radiation heat loss cannot reproduce a correct flame ball limit and flame size. Abbud-Madrid and Ronney (1993) used a particle laden flame to measure the enhancement of burning velocity to explore the radiation absorption effect. However, due to the particle heat capacity and the inhomogeneous particle concentration, radiation absorption effect was not successfully observed.

Despite of above mentioned studies, the quantitative and even qualitative effects of spectral radiation absorption on flame propagation, extinction, and instability, particularly for near limit premixed flames are far from being understood. Few experimental studies have been conducted to investigate the effect of radiation absorption on the burning properties and flammability limit of CO<sub>2</sub> added mixtures. The objective of the present research is to experimentally investigate the effects of non-gray gas radiation reabsorption on near limit flame propagation using CO<sub>2</sub> diluted outward propagating flames at normal gravity, to provide experimental data for radiation and kinetic model validation. Flame speeds of CO<sub>2</sub> diluted CH<sub>4</sub>-O<sub>2</sub>-He mixture at elevated pressures up to 5 atm were measured by using a pressure-release type spherical bomb. The measured data were compared with the results from computations performed without considering radiation (adiabatic, ADI), with radiation employing optically thin model (OTM), and with radiation utilizing a detailed emission/absorption statistical narrow band (SNB) model.

## Experimental and Numerical Methods

Details of the design and operation of the dual-chambered, pressure-release type high pressure combustion facility can be found in (Qin and Ju 2004). 1-D, steady, planar premixed flames were simulated using a CHEMKIN-based code (Kee et al. 1985) with arc-length continuation and detailed chemistry, transport and (optically thin and optically thick) radiation models. For the optically thin radiation simulations,  $\text{CO}_2$ ,  $\text{H}_2\text{O}$ ,  $\text{CO}$  and  $\text{CH}_4$  are considered as the most important radiating species. For optically thick radiation, radiative transport including both emission and absorption was computed using the statistical narrow band model (SNB) with exponential-tailed inverse line strength distribution. Methane oxidation was modeled using GRI-MECH 3.0 mechanism by deleting species and reactions related to  $\text{NO}_x$  formation. Mixtures of  $\text{CH}_4$ -air and  $\text{CH}_4$ - $\{0.3\text{O}_2+0.2\text{He}+0.5\text{CO}_2\}$  were examined.

## Preliminary Results

Figure 1 shows the measured 1-g laminar burning velocities of  $\text{CO}_2$  diluted flames at different pressures. The calculation results from optically thin and SNB model are plotted in lines. Since no other data are available, we only compare the measured data with computed results. The measured data agree well with predictions for equivalence ratio larger than 0.6. The downward flammability limits  $\Phi_d$  for these mixtures at 1, 2 and 5 atm are 0.50, 0.52 and 0.57, respectively. The increase of  $\Phi_d$  to higher equivalence ratio with increasing pressure is consistent with the results of Ronney and Wachman (1985). This increase is mainly due to the enhanced buoyancy effect at high pressures. The SNB calculation gives higher flame speed data than adiabatic situation because of reabsorption effect. Different from undiluted  $\text{CH}_4$ -air flames, the measured  $\Phi_d$  of  $\text{CO}_2$  diluted flames outreach the prediction from the optically thin model and the flame speed data are higher than those from optically thin model, but still lower than those from adiabatic and SNB predictions. This suggests that for  $\text{CO}_2$  diluted

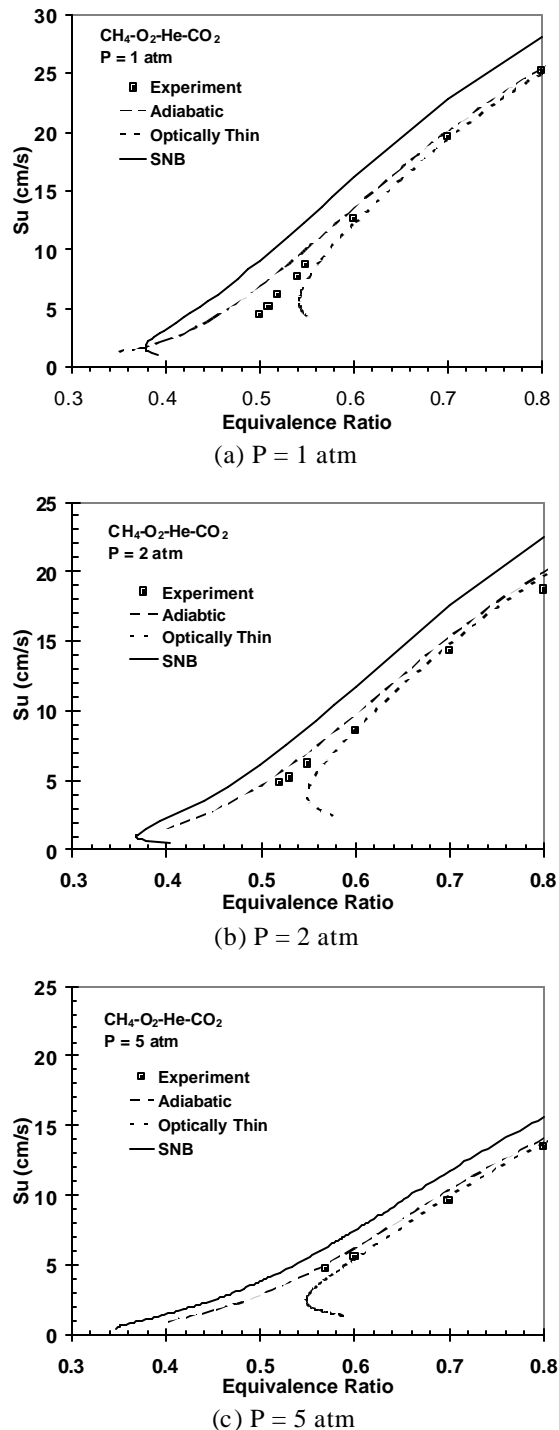


Figure 1. Flame speeds of  $\text{CH}_4$ - $\text{O}_2$ - $\text{He}$ - $\text{CO}_2$  flames at various pressures.

flames, the reabsorption effects enhance the flame propagation and extend the flammability limit. It is also seen from Fig. 1 that the flammability limits predicted by SNB model extend to lower equivalence ratio at high pressure. This is consistent with theory since optical thickness increases with increasing pressure.

Figure 2 shows the optical thickness of diluted and undiluted CH<sub>4</sub> mixtures. It can be seen that the optical thickness of CH<sub>4</sub>-air mixtures is much smaller than unity, and thus the CH<sub>4</sub>-air flames can be regarded as optically thin and reabsorption effects are not significant. However, for CO<sub>2</sub> diluted mixtures, the optical thickness is much larger than unity and the flames are optically thick. Therefore, reabsorption effects are obvious and must be considered in the calculation. Figure 3 shows radiative power  $Q_R$  and temperature distribution along spatial coordinate for a CH<sub>4</sub>-O<sub>2</sub>-He-CO<sub>2</sub> flame at  $\phi = 0.6$  from different radiation models. When reabsorption is considered,  $Q_R$  is negative at  $x < 0.16$  because some energy radiated from high temperature zone is reabsorbed at lower temperature region. The unburned mixture is preheated by reabsorption and net loss due to radiation decreases. The maximum temperature in SNB exceeds the adiabatic temperature and decreases slow downstream in a large scale. While with optically thin radiation, the peak temperature decays rapidly downstream. The reabsorbing flame also has a longer upstream convective-radiative zone. From these observations, it can be concluded that reabsorption enhances flame propagation and extends flammability limit.

## Conclusions

Laminar burning velocities of CO<sub>2</sub> diluted CH<sub>4</sub>-O<sub>2</sub>-He mixture at both normal and elevated pressures up to 5 atm were measured by using a pressure-release type spherical bomb. The measured data were compared with the results from computations performed without considering radiation, with radiation employing optically thin model, and with radiation utilizing a detailed emission/absorption statistical narrow band model. The effects of radiation reabsorption on near limit of CO<sub>2</sub> diluted outward propagating flames at normal gravity were studied. It was found that reabsorption can increase burning velocities of CH<sub>4</sub>-O<sub>2</sub>-He-CO<sub>2</sub> mixtures and extend flammability limits. Reabsorption effects increase with the increase of pressure. For optically

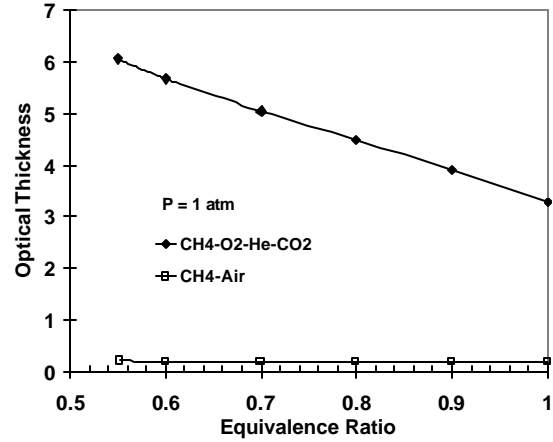


Figure 2. Optical thickness of CH<sub>4</sub> mixtures.

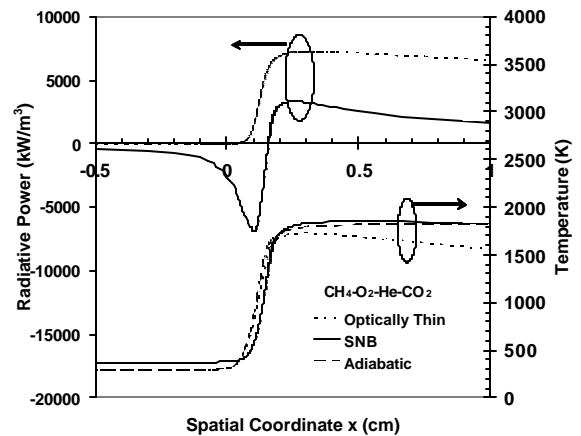


Figure 3. Radiative power and temperature distribution along spatial coordinate for a CH<sub>4</sub>-O<sub>2</sub>-He-CO<sub>2</sub> flame at  $\phi = 0.6$  from different radiation models.

thick flames with CO<sub>2</sub> dilution, reabsorption effects must be considered to correctly predict flame speeds and extinction limits in simulation. For future work, experimental measurements of transmissivity of the CO<sub>2</sub> diluted mixture will be measured before and after flame initiation. The spherical flame experiment could provide another way to measure the spectral transmissivity of the burned gas at high pressure. Moreover, simulation of the spherically propagating flame instead of steady planar flame is also preferred.

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