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Computed flammability limits of opposed-jet H_2/CO syngas diffusion flames

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ABSTRACT

Extensive computations were made to determine the flammability limits of opposed-jet H_2/CO syngas diffusion flames from high stretched blowoff to low stretched quenching. Results from the U-shape extinction boundaries indicate the minimum hydrogen concentrations for H_2/CO syngas to be combustible are larger towards both ends of high strain and low strain rates. The most flammable strain rate is near one s^{-1} where syngas diffusion flames exist with minimum 0.002% hydrogen content. The critical oxygen percentage (or limiting oxygen index) below which no diffusion flames could exist for any strain rate was found to be 4.7% for the equal-molar syngas fuels (H_2/CO = 1), and the critical oxygen percentage is lower for syngas mixture with higher hydrogen content. The flammability maps were also constructed with strain rates and pressures or dilution gases percentages as the coordinates. By adding dilution gases such as CO_2, H_2O, and N_2 to make the syngas non-flammable, besides the inert effect from the diluents, the chemical effect of H_2O contributes to higher flame temperature, while the radiation effect of H_2O and CO_2 plays an important role in the flame extinction at low strain rates.

1. Introduction

Syngas or synthetic gas, which is mainly composed of H_2 and CO, can be obtained from many kinds of fossil fuels and solid combustibles, such as coal, biomass, refinery residual and municipal waste through gasification processes [1]. In recent years, syngas is being recognized as a viable energy source and an attractive fuel, particularly for stationary power generation with IGCC (Integrated Gasification Combined Cycle) technology [2,3]. As the energy demand and environmental concerns continue to grow, syngas is expected to be one of the promising fuels in future energy production. However, the syngas composition and relative amount of the constituents may vary depending on the fuel sources and the gasification processes. There is considerable variation of H_2/CO ratio with the rest being primarily N_2, CO_2, and H_2O. This wide variation in syngas composition has a direct impact on the combustion and extinction characteristics, which will be a challenge in designing syngas combustors and applying syngas fuels. Due to the presence of hydrogen, syngas or syngas-hydrocarbon mixtures could be a proposal of the extension of flame stability limit, improvement of performance and the reduction of emissions in lean combustion systems, especially for H_2-enriched syngas fuels [4–6]. On the other hand, a wide flammable range of syngas fuels is considered a drawback in the fire safety aspect. To prevent accident explosions and fires from occurring in the processes, the flammable range of syngas mixture must be known, and the study of flame extinction and flammability limits are important.

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Nomenclature

a	strain rate (radial velocity gradient on the fuel side)
c_p	constant-pressure specific heat
D_{kj}	multi-component diffusion coefficient
D^T	thermal diffusion coefficient
h	enthalpy
I	radiative intensity
P	total pressure
pl	pressure path length
q_i	net reaction rate or the rate-of-progress variable
q_r	radiative heat flux
R_u	universal gas constant
RIF	reaction impact factor
s, s'	direction along a ray
T	temperature
U	nondimensional radial velocity
V	axial mass flux
ν	diffusion velocity
W	molecular weight
X	mole fraction or broadening equivalent width
Y	mass fraction
y	axial direction
β	mean line width to spacing ratio
γ	line half-width
δ	line spacing parameter
k	mean absorption coefficient
λ	heat conduction coefficient
μ	viscosity or direction cosine
ν	wave number
w	quadrature weights
ρ	density
τ	transmittance
$\dot{\omega}$	chemical production rate
Ω	solid angle

Subscripts

b	blackbody
C	collision
D	Doppler
i	reaction step index
k	species index
ν	wave number
w	wall quantity (radiation boundary)
$+\infty$	oxygen side
$-\infty$	fuel side

Superscripts

$+$	forward reaction or positive
$-$	reversed reaction or negative

Several prior research works have focused on the flame structures and NO_x emission characteristics of counterflow diffusion flames considering various syngas compositions, dilution gases, and operation conditions such as pressures and strain rates [7–10]. For example, Drake and Blint [7] numerically studied the flame structures and the effects of strain rates on NO emissions of laminar opposed-flow diffusion flames with $CO/H_2/N_2$ fuels. Giles et al. [8] also numerically investigated the NO_x emission characteristics of counterflow syngas diffusion flames with dilution gases such as N_2, H_2O, and CO_2 on the airstream. Som et al. [9] then further conducted numerical and experimental study of the counterflow syngas flames for different fuel compositions and pressures. To consider the flame extinction, Park et al. [10] examined the chemical effects and radiative loss effects of added CO_2 on syngas flame structures and flame extinction, indicating the profound combustion and extinction characteristics of syngas due to its variable compositions and operation conditions.

Recently, Shih and Hsu [11,12] numerically studied opposed-jet syngas diffusion flames with detailed chemical kinetics, thermal and transport properties and flame radiation calculated by narrowband radiation model. The combustion, extinction, and emission characteristics of opposed-jet syngas diffusion flames at low strain rate (10 s^{-1}) were investigated. Although some flame extinction limits due to low hydrogen content, low pressure and dilution gases were found, the flammability limits over a wide range of flammable strain rates from quenching to blowoff are not completed. In this work, the flame extinction limits are obtained for both high-stretch blowoff, where the flame goes out because of insufficient gas residence time for chemical reaction, and for the low-stretch flame quenching due to radiative heat loss. The flammability maps are numerically constructed with the flammable strain rates versus syngas compositions, pressures, and dilution gas percentages as the coordinates. The effects of hydrogen percentage of syngas, oxygen concentration, ambient pressure, and dilution gases on the flammability limits of H_2/CO syngas diffusion flames are also examined.

2. Mathematical and numerical models

2.1. *Opposed-jet diffusion flames*

Assuming a counterflow, axisymmetric laminar diffusion flame stabilized near the stagnation plane of two opposing jet flows, as shown schematically in Fig. 1, two equivalent

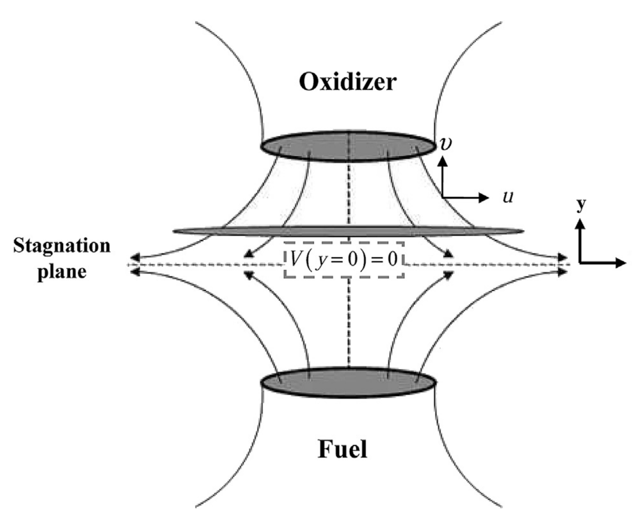

Fig. 1 – Schematic of opposed-jet diffusion flame.