Combustion and Flame 161 (2014) 2890–2903

Contents lists available at ScienceDirect

Combustion and Flame

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

Liftoff heights of turbulent non-premixed flames in co-flows diluted by CO_2/N_2

Yuzuru Nada [a,*], Kazuo Matsumoto [b], Susumu Noda [b]

[a] Department of Energy System, The University of Tokushima, 2-1 Minami-Josanjima, Tokushima 770-8506, Japan
[b] Department of Mechanical Engineering, Toyohashi University of Technology, 1-1 Hibarigaoka, Tempaku, Toyohashi 441-8580, Japan

ARTICLE INFO

Article history:
Received 25 October 2013
Received in revised form 31 January 2014
Accepted 12 May 2014
Available online 3 July 2014

Keywords:
Turbulent lifted flame
Dilution
Entrainment
Liftoff height
Premixed model
Large eddy model

ABSTRACT

The objective of this study was to propose a new model for the prediction of the liftoff heights of turbulent flames diluted by the entrainment of burned gases. In combustion furnaces with the internal recirculation of burned gases, mixtures of fuel and oxidizer are diluted with recirculated burned gases through entrainment into the gas jets. We focused on the effects which dilution resulting from entrainment has on the stabilization mechanism of lifted flames. In order to investigate the effects of dilution on liftoff height, we employed a concentric burner incorporating fuel, oxidizer and co-flow gas nozzles. The recirculated burned gas was simulated by co-flow air diluted with either N_2 or CO_2 gas. Liftoff heights were observed to increase with decreasing O_2 concentrations in the co-flow gas when maintaining a constant O_2 concentration in the oxidizer, due to dilution resulting from entrainment of the diluted co-flow gas. The liftoff heights obtained with co-flow gases diluted by CO_2 were greater than those obtained when diluting with N_2 due to both thermal and chemical dilution effects. The conventional premixed model was not able to predict the liftoff trends observed in this study and we therefore propose a modified premixed model which takes into account the dilution effect resulting from entrainment. In this model, the amount of entrained co-flow gas is evaluated according to the self-similarity law of a round jet. Non-dimensional liftoff heights based on this modified model exhibit excellent linear correlation with non-dimensional fuel gas velocities, even when various co-flow gases are used for dilution. The conventional large eddy model was also modified in the same manner and the results obtained from the modified model exhibit satisfactory correlation.

1. Introduction

Combustion technologies based on dilution of the combustion mixture with recirculated burned gases are a useful means of reducing NO_x and soot emissions from combustion furnaces. MILD combustion [1] is a representative reduction technology which is also sometimes referred to as high temperature air combustion [2] or flameless oxidation [3]. In MILD combustion furnaces, the fuel gas and oxidizer are generally supplied from separate nozzles into the furnace as high speed jets, after which each gas mixes with recirculated burned gas through entrainment by each jet until the bent fuel jet merges with the oxidizer jet [4,5]. Mixing with the recirculated burned gas dilutes both the fuel gas and the oxidizing gas while simultaneously raising the temperatures of the diluted gases, thus achieving a uniform temperature distribution throughout the furnace and allowing a low flame temperature, which reduces NO_x emissions through the Zel'dovich mechanism [6].

In general, there are three fundamental effects of dilution in terms of reducing NO_x and soot emissions: the pure dilution, thermal and chemical effects [7,8]. The pure dilution effect is due to the reduction of reactant concentrations resulting from mixing with burned gases, while the thermal effect results from the greater specific heat of CO_2 compared to that of air, since an increase in the specific heat reduces the flame temperature. The chemical effect is caused by modification of the equilibrium state in some chemical reactions; the addition of CO_2 to the oxidizer, for example, increases the extent of the reaction $CO_2 + H \rightarrow CO + OH$, thus decreasing combustion intensity.

Additional NO_x reduction technologies which are also based on dilution are still being developed [9,10]. Noda et al. [10] investigated the effects of burned gas dilution on NO_x emissions from laboratory-scale cylindrical furnaces which incorporated a triple concentric burner supplying fuel and oxidizer at different initial velocities. In these furnaces, a concentric jet entrains the burned

* Corresponding author. Fax: +81 886569124.
E-mail address: ynada@tokushima-u.ac.jp (Y. Nada).

http://dx.doi.org/10.1016/j.combustflame.2014.05.007
0010-2180/

Nomenclature

A	parameter used in Eq. (4) describing the decay of streamwise velocity
B	parameter used in Eq. (5) describing the evolution of the jet half-width
d	inner diameter of the nozzle
d_{ef}	effective diameter of the fuel nozzle
H	mean liftoff height
K	dilution ratio
K_m	mixture dilution ratio (volume ratio of diluents to mixture)
l	integral length scale
L_u	jet half-width
M	mass flow rate
m_i	mass of gas i in a fluid
Re	Reynolds number
r	radial coordinate
r_I	radius of a cylindrical control volume
S_L	laminar burning velocity
S_T	turbulent burning velocity
T_{hr}	threshold value for binarization
u	streamwise velocity
u'	root mean square fluctuation velocity
U	bulk velocity
x	axial coordinate
X	volume fraction
Y_i	mass fraction of species i
Z_i	mixture fraction of gas i
α	thermal diffusivity
β	mass flow rate ratio of fuel gas to oxidizer (= M_O/M_F)
κ	density ratio of fuel gas to ambient gas
ν	viscosity
ρ	density
θ	azimuthal coordinate
ζ	distance from a virtual origin

Subscripts

0	jet axis
C	co-flow gas
E	gas flowing out from control volume
EN	entrained co-flow gas
F	fuel gas
K	diluted gas
O	oxidizer
$O2$	oxygen
st	stoichiometric condition

Superscript

$*$	relative value to co-flow gas

gas as it is recirculated upstream by vortices formed in the lower section of the furnace. The reactants and the entrained burned gas are mixed with one another in the mixing layer of the jet and thus both the fuel and the oxidizer are diluted with the burned gas. The Noda study found that NO_x emissions from the diluted flames can be correlated with the Reynolds number based on the furnace's inner diameter, which is a measure of the quantity of entrained burned gas. This successful scaling of the NO_x emissions demonstrates the importance of dilution through entrainment with regard to the NO_x emissions characteristics of furnaces with recirculation vortices.

The entrainment of hot recirculated burned gas stabilizes a flame due to the temperature rise of the diluted reactant gases [11] while simultaneously destabilizing the flame via dilution effects [12–14]. In the present study, we examine the effects of dilution resulting from entrainment on flame stability. Many researchers have previously investigated dilution effects on flame stability; Min and co-workers investigated dilution effects on flame lifting from a burner rim both experimentally [12] and theoretically [13], using different oxidizing gas mixtures containing CO_2, N_2 and Ar. This work demonstrated that dilution with CO_2 has the greatest influence on flame lifting. Moreover, the contribution of the pure dilution effect to flame lifting was found to be the most significant, followed by the thermal effect, while the chemical effect is relatively small. Min and Baillot [14] also demonstrated that oxidizer dilution (which they term air-side dilution) with CO_2 increases the liftoff height by reducing the flame propagation speed, indicating the significant influence of dilution on the stability of the lifted flame. Other researchers have investigated fuel dilution effects on liftoff height [15–19], and have demonstrated that fuel dilution increases liftoff height as well as the oxidizer dilution. Min and Baillot [14] also concluded that the influence of oxidizer dilution is greater than that of fuel dilution based on liftoff height scaling. Lock et al. [20] explained the differing effects of fuel and oxidizer dilution on blowout characteristics in terms of deficient reactant quantities.

In previous studies [12–20], dilution effects on liftoff heights were investigated using dual concentric burners in which either the fuel or the oxidizer is pre-diluted before being released. In contrast, combustion furnaces with burned gas recirculation dilute the fuel and oxidizer via entrainment by each jet. The amount of ambient gas entrained into a main jet is known to be proportional to the distance from the virtual origin of the jet [21], which indicates that the extent of dilution increases with increasing distance from the burner exit. The burned gas dilution responsible for increasing liftoff height occurs in the region from the nozzle exit to the flame base, and hence an increase in the liftoff height results in enhanced dilution, leading to a further increase in the liftoff height. In prior research [12–20], the effects of initial temperature and reactant concentrations on liftoff height were investigated. Even though these studies contributed significantly to the modeling of lifted flames, they were not aimed at elucidating the relationship between the liftoff height and the dilution level and thus did not do so.

Predictions of liftoff heights and blowout limits have continued to be the main subjects of combustion research in recent years since flame stabilization is essential for safe combustion. A number of prediction models were proposed by previous studies [22,23], and can be roughly classified as the extinction, premixed and large eddy models [22]. Peters and Williams [24] applied the local extinction theory for laminar diffusion flame when studying the flame lifting mechanism. In their extinction model, liftoff height is deemed to be the length of the region in which flame extinction occurs due to pronounced flame stretch, and thus this height is expressed as a function of the critical scalar dissipation rate for local extinction of laminar flamelets. However, many results obtained from laser diagnostics (see, for example, Ref. [25]) support a different stabilization mechanism based on flame