EFFECT OF BURNER DIAMETER AND DILUENTS ON STRUCTURE AND STABILITY OF LAMINAR CO-FLOW DIFFUSION FLAMES OF DILUTED METHANE FUEL

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by

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submitted

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Dedicated to

My mother Mrs. Prabha Mishra

My father Mr. Shiv Kumar Mishra

My eldest brother Mr. Prashant Mishra

My wife Dr. Anjali Dwivedi

CERTIFICATE

The thesis entitled "**Effect of Burner Diameter and Diluents on Structure and Stability of Laminar Co-flow Diffusion Flames of Diluted Methane Fuel**" being submitted by **Mr. Anurag Mishra** to the Indian Institute of Technology Delhi for the award of the degree of **Doctor of Philosophy** is a record of original bonafide research work carried out by him. He has worked under our guidance and supervision and has fulfilled the requirements for the submission of this thesis, which has attained the standard required for a Ph.D. degree of this Institute. The results represented in this thesis have not been submitted elsewhere for the award of any degree or diploma.

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ABSTRACT

Low calorific value gases (LCVG) have been a primary concern of environmental pollution as they are not easy to burn due to highly diluted fuel compositions. It is thus essential to understand the flame characteristics when these gases are burnt, especially under oxygen enhanced conditions. Although the study of stoichiometric flame lengths of laminar jet or co-flow diffusion flames has been a major topic of research in last few decades, mostly focusing on flames of either undiluted or slightly diluted fuel reacting with air. However, the flame characteristics under extremely diluted fuel conditions are not well-studied. Hence, a set of experiments and numerical simulations have been performed in the present work to study the flame lengths for a wide range of fuel and oxidizer dilutions using two different jet diameter burners (4 and 9 mm with identical volume flow rates). Both experimental and numerical results confirm that the 4 mm burner flame length is consistently higher than the 9 mm burner counterpart. This difference is attributed to the higher temperature of the 9 mm burner flame, which in turn is due to its lower conductive heat loss to the ambient. Several analytical models, available in the literature to predict the flame lengths, such as Roper, Li-Gordon-Williams (LGW), and Wang-Sunderland-Axelbaum (WSA), have also been analyzed and compared with the experimental data. A new analytical model is also proposed in this study by modifying the species diffusivity and flame temperature in WSA model. This revised model predicts the flame lengths better than the other analytical models, especially when the fuel stream is diluted.

Apart from the flame length, the understanding of lifted flame stabilization is important in the context of highly diluted flames as well. Laminar flames of highly diluted methane in a non-premixed co-flow configuration have been studied experimentally and numerically for two different diameter burners (4 and 9-mm). Because the fuel is extremely diluted methane, an oxygen-enhanced oxidizer stream is expected to produce a stable anchored or lifted flame. Two different diluents, i.e., helium and nitrogen were used in the fuel stream, and the flame structure

turned out to be notably different for these two cases. The nitrogen-diluted flames exhibited almost anchored nature. However, a helium-diluted flame could be stable at a lifted position despite having a less than unity Schmidt number (Sc). This difference is attributed to the difference in propagation speed between helium and nitrogen-diluted flames due to mixture fraction gradient, flame curvature and heat release impact. In comparison to nitrogen-diluted flames, helium-diluted flames can sustain at lower oxygen percentage due to a higher propagation speed. Apart from the difference in lift-off height, the nature of the flame length is also explored for flames with both the diluents. The structure of the flame – whether anchored or lifted – is also found to affect the variation of flame length with variation in oxygen percentage in the co-flow. A comparison between two different diameter burners is also investigated in terms of lift-off height and flame length. The 4-mm burner usually exhibits a higher lift-off than the 9-mm burner due to the higher jet velocity in the former case.

सार

कम कैलोरी मान वाली गैसें (LCVG) पर्यावरण प्रदूषण की प्राथमिक चिंता रही हैं क्योंकि अत्यधिक तनुकृत ईंधन संघटनों के कारण इन्हें जलाना आसान नहीं है। इसलिए जब इन गैसों को जलाया जाता है, विशेष रूप से ऑक्सीजन की बढ़ी हुई परिस्थितियों में, फ्लेम की विशेषताओं को समझना आवश्यक है। हालांकि लैमिनार जेट या को-फ्लो डिफ्यूज़न फ्लेम के लिए स्टोइकोमेट्रिक फ्लेम की लंबाई का अध्ययन पिछले कुछ दशकों में शोध का एक प्रमुख विषय रहा है जो कि ज्यादातर हवा के साथ प्रतिक्रिया करने वाले या तो बिना तनुकृत या थोड़े तनुकृत ईंधन की फ्लेम्स पर ध्यान केंद्रित करता है। हालांकि, अत्यधिक तनुकृत ईंधन स्थितियों के तहत फ्लेम विशेषताओं का अच्छी तरह से अध्ययन नहीं किया गया है। इसलिए, दो अलग-अलग व्यास के जेट बर्नर (4 और 9 मिमी बर्नर में समान फ्लो रेट के साथ) का उपयोग करके ईंधन और ऑक्सीडाइज़र की विस्तृत श्रृंखला के लिए फ्लेम की लंबाई का अध्ययन करने के लिए वर्तमान कार्य में प्रायोगिक और संख्यात्मक सिमुलेशन दोनों किये गए है। प्रायोगिक और संख्यात्मक सिमुलेशन से प्राप्त हुए परिणाम इस बात की पुष्टि करते हैं कि 4 मिमी बर्नर की फ्लेम की लंबाई 9 मिमी बर्नर की तुलना में अधिक है। यह अंतर 9 मिमी बर्नर की फ्लेम के उच्च तापमान कि वजह से है, उच्च तापमान कि वजह कम कंडक्टिव हीट लॉस का होना है। फ्लेम की लंबाई निकालने के लिए साहित्य में उपलब्ध कई विश्लेषणात्मक मॉडल, जैसे रोपर, ली-गॉर्डन-विलियम्स (LGW), और वांग-सुंदरलैंड-एक्सेलबाउम (WSA) का भी विश्लेषण किया गया है और प्रायोगिक डेटा के साथ तुलना की गई है। इस अध्ययन में WSA मॉडल में स्पीशीज के डिफ्यूज़न और फ्लेम तापमान को संशोधित करके एक नया विश्लेषणात्मक मॉडल भी प्रस्तावित किया गया है। यह संशोधित मॉडल अन्य विश्लेषणात्मक मॉडलों की तुलना में फ्लेम की लंबाई को बेहतर बताता है, खासकर जब ईंधन तनुकृत होता है।

फ्लेम की लंबाई के अलावा, अत्यधिक तनुकृत ईंधन के लिए लिफ्टेड फ्लेम्स की स्थिरीकरण को समझना महत्वपूर्ण है। लैमिनार को-फ्लो डिफ्यूज़न विन्यास में अत्यधिक तनुकृत मीथेन फ्लेम्स का दो अलग-अलग

व्यास वाले बर्नर (4 और 9-मिमी) में प्रयोगात्मक और संख्यात्मक अध्ययन किया गया है। क्योंकि ईंधन अत्यंत तनुकृत है, एक ऑक्सीजन-वर्धित ऑक्सीडाइज़र फ्लो से एक स्थिर अटैच्ड या लिफ्टेड फ्लेम प्राप्त होने की उम्मीद है। ईंधन के फ्लो में दो अलग-अलग तनुकृत, यानी हीलियम और नाइट्रोजन का उपयोग किया गया है, और इन दोनों के लिए फ्लेम की संरचना उल्लेखनीय रूप से भिन्न थी। नाइट्रोजन- तनुकृत के साथ अटैच्ड फ्लेम प्राप्त हुई है। हालांकि, हीलियम-तनुकृत के साथ Sc संख्या एक से कम होने के बावजूद एक हाइट पर स्थिर हो सकती है। यह अंतर हीलियम और नाइट्रोजन-तनुकृत फ्लेम्स कि अलग-अलग प्रोपोगेशन स्पीड कि वजह से है। नाइट्रोजन-तनुकृत फ्लेम्स की तुलना में, ज्यादा प्रोपोगेशन स्पीड के कारण हीलियम-तनुकृत फ्लेम्स कम ऑक्सीजन प्रतिशत पर बनी रह सकती हैं। लिफ्ट-ऑफ हाइट में अंतर के अलावा, दोनों तनुकारकों के साथ फ्लेम की लंबाई की प्रकृति का भी पता लगाया जाता है। फ्लेम की संरचना-चाहे स्थिर हो या लिफ्टेड हो – को-फ्लो में अलग-अलग ऑक्सीजन प्रतिशत के साथ फ्लेम की लंबाई भी प्रभावित होती है। लिफ्ट-ऑफ हाइट और फ्लेम की लंबाई को समझने के लिए दो अलग-अलग व्यास बर्नर के बीच तुलना कि गयी है। ज्यादा जेट वेग के कारण 4-मिमी बर्नर आमतौर पर 9-मिमी बर्नर की तुलना में ज्यादा लिफ्ट-ऑफ हाइट दिखाता है।

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Nomenclature

X	axial location (m)	r	radial location (m)
Z	mixture fraction	ρ_F	mean flame density (kg/m^3)
Z_{st}	stoichiometric mixture fraction	ρ_{cf}	the density of co-flow mixture (kg/m^3)
d, r_o	burner diameter, the radius of the fuel nozzle (m)	T_F	mean flame temperature
Q_f	volumetric flow rate of fuel (m^3/sec)	T_∞	ambient temperature
$u_{f,o}$	fuel nozzle exit velocity (m/sec)	Y_f	fuel jet mass fraction at location (x, r)
G	acceleration due to gravity (m^2/sec)	Y_o	co-flow oxidizer mass fraction at location (x, r)
Ri	Richardson number, $Ri = (\rho_{cf} - \rho_F)gd/ (\rho_F u^2_{f,o})$	$Y_{f,o}$	fuel jet mass fraction at nozzle exit
υ_f	Kinematic viscosity of the fuel	$Y_{o,o}$	oxidizer mass fraction at co-flow exit
Re	Reynolds number, $Re = u_{f,o}\, d/\upsilon_f$	X_{O2}	mole fraction of oxygen
l_F	Flame length (m)	X_{N2}	mole fraction of nitrogen
D_o	Diffusion coefficient (m^2/sec)	f_v	soot volume fraction
X_{CH4}	mole fraction of methane	T	local flame temperature (K)
T_{ad}	adiabatic flame temperature (K)	σ	Stefan-Boltzman constant (5.67×10^{-8} w/m^{2}K^4)
p_i	the partial pressure of species i	T_f	the characteristic temperature of the flame

a_i	Planck mean absorption coefficient for species i	S	the ratio of the volume of ambient gas to the volume of burner gas for stoichiometric combustion
ϕ	equivalence ratio	s	the ratio of the mass of ambient gas to the mass of burner gas for stoichiometric combustion
$X_{o,o}$	mole fraction of oxygen in the oxidizer stream	k	thermal conductivity of gases close to the edge of the flame (W/m/ K)
H_L	Lift-off height	α	heat release rate
S_L	laminar burning velocity (m/sec)	Se	propagation speed (m/sec)
B	Zeldovich number	χ_s	scalar dissipiation rate (sec^{-1})
LBV	Laminar burning velocity (m/sec)	Subscript	
MFCs	Mass flow controllers	F	Flame
Fr	Froude number	∞	Ambient
NDF	Normal diffusion flame	o	The initial condition of the fuel
$\dot{m}_{ox}$	total flow rate of oxidizer (kg/sec)	st	stoichiometric
CFD	computational fluid dynamics	ad	adiabatic
c_p	specific heat of fuel gases (J/kg.K)	b	burnt gas