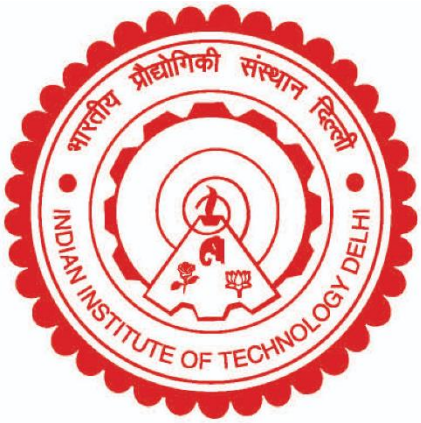
A NEW METHODOLOGY FOR DETERMINATION OF LAMINAR BURNING VELOCITY IN A CYLINDRICAL VESSEL WITH FULL OPTICAL ACCESS USING CONSTANT VOLUME METHOD

VIKAS JANGIR



DEPARTMENT OF MECHANICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI

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by

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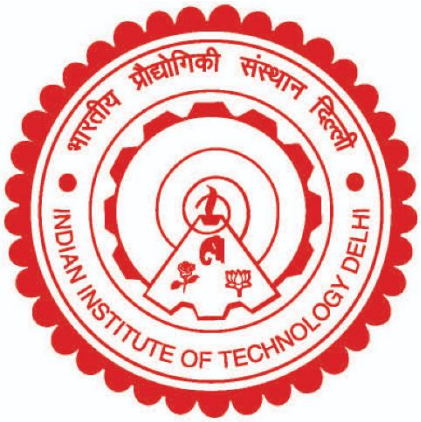
Department of Mechanical Engineering

submitted

in fulfillment of the requirements of the degree of

DOCTOR OF PHILOSOPHY

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

MAY 2023

Dedicated to

My mother Mrs. Sushila Devi and father Mr. Rajendra Prasad Jangir,

and

to my wife Mrs. Kanak Lata and my daughter Anvi Jangir.

Certificate

This is to certify that the thesis entitled "**A New Methodology for Determination of Laminar Burning Velocity in a Cylindrical Vessel with Full Optical Access Using Constant Volume Method**" being submitted by **Mr. Vikas Jangir** (2016MEZ8547) to the Indian Institute of Technology Delhi, New Delhi, for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him under our supervision. The candidate has fulfilled the requirements for the submission of this research work for his thesis. In our opinion, this thesis has attained the standard needed for the award of a Ph.D. degree of this institute. The results contained in this thesis have not been submitted, in a part or in full, to any other university or institute for the award of any degree or diploma.

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Abstract

Laminar burning velocity is a fundamental property of a fuel-air mixture at a given pressure, temperature and equivalence ratio. Many practical combustion appliance designs are based on the laminar burning velocity. It is also a strong candidate to validate or develop chemical kinetic models. The laminar burning velocity is also an important input in modelling turbulent premixed combustion in spark ignition engines. Therefore, its accurate measurement is necessary. The constant volume method is the only technique suitable for determining laminar burning velocity at engine-relevant thermodynamic conditions. Values of laminar burning velocity obtained by the conventional constant volume method suffer from the inaccuracies induced by the weak burned gas mass fraction model and the effect of flame stretch. Direct measurement of the flame radius along with pressure-time trace can result in accurate determination of laminar burning velocity in constant volume method. This motivates the present work to look closely at the constant volume method with a view to improve its accuracy/eliminate its weaknesses.

A spherical chamber would be the best choice for the constant volume method, as in such chambers, the flame remains spherical throughout the combustion. However, full optical access in a spherical chamber may produce lens effect due to the curvature of chamber walls, and would need an optical correction to get the correct flame radius. Spherical transparent chambers are also difficult to fabricate. The remedy for this is the use of flat optical windows. Use of flat optical windows in a spherical chamber restricts the useful range of the flame radius-time data. The other alternative is to the use a cylindrical chamber with full flat optical windows. Such a combustion chamber gives direct visual access to the entire range of flame radii in the chamber, and can also help in detecting the onset of cellularity. A cylindrical combustion chamber with full optical access is also easy to fabricate.

Since the flame in a cylindrical vessel does not remain spherical throughout the period of propagation, the end-view radius obtained during the experiment cannot be used directly to compute the actual burned gas volume and flame surface area. The current work proposes a new methodology for determining accurate values of laminar burning velocity in a cylindrical vessel using constant volume method. A comprehensive numerical simulation of constant volume combustion in a cylindrical and spherical chamber is performed using computational fluid dynamics (CFD). Two normalized relations in a cylindrical vessel are developed using CFD simulations. The relationship obtained by numerical simulation between the normalized

radius of the end-view of the flame, $\left(R_{f,end-view}/R_c\right)$ and the normalized burned gas volume (V_b/V_t) as well as the normalized flame surface area $\left(A_f/A_t\right)$ in a cylindrical chamber is found to be purely geometric, and hence is independent of the fuel-air mixture and chamber size, so long as its aspect ratio is unity. Using these relationships, end-view of flame radius, $R_{f,end-view}$, can be mapped to correct burned gas volume and flame surface area in a cylindrical vessel of any size. Then, using burned gas volume, flame surface area and pressure-time trace, laminar burning velocity can be accurately calculated at each location of the flame without the need for a model for burned gas volume.

Firstly, the pressure-time trace and end-view flame radius obtained from numerical simulations, in combination with the mapping approach, are used to calculate laminar burning velocity using constant volume method. The obtained values of laminar burning velocity in a cylindrical vessel are identical to those obtained numerically in a spherical vessel. Second, using the proposed method, obtained values of laminar burning velocity are also corrected for flame stretch. A stretch-correction methodology requires the values of laminar burning velocity with different stretch rates at a given target state (p, T) of the mixture, for extrapolating the laminar burning velocity to zero stretch. Stretch-corrected values of laminar burning velocity obtained in a cylindrical vessel for a $H_2 + O_2$ −diluent mixture at various equivalence ratios are in good agreement with those obtained in a spherical chamber.

The new methodology proposed using numerical simulation is demonstrated for experimental data for methane-air mixture. This starts with developing a new cylindrical combustion chamber of volume 10.86 litre with full optical access and heating arrangement. Using the experimentally recorded pressure-time trace, end-view of flame radius and mapping methodology, the laminar burning velocity for a stoichiometric methane-air mixture is determined using the constant volume method, and the results agree well with those of a previously published study. The present work also demonstrates the stretch-correction method, originally proposed by the author's research group [99], for methane-air flames for pressures up to 2.5 bar, for equivalence ratio 0.8 – 1.2. Thus, the present work significantly reduces the main drawbacks of the constant volume method, making the method a candidate for accurate determination of laminar burning velocity.

सार

लैमिनार बर्निंग वेलोसिटी (LBV) दिए गए दाब, तापमान और समतुल्य अनुपात पर ईंधन-हवा के मिश्रण का एक मौलिक गुण है। कई दहन सम्बंधित उपकरणों की सरंचना LBV पर आधारित है। इसका प्रयोग रासायनिक गतिज मॉडलों की पुष्टि या उन्हें विकसित करने के लिए किया जाता है। स्पार्क प्रज्वलन इंजन में होने वाले टर्बुलेंट प्रीमिक्सिड दहन की मॉडलिंग के लिए LBV का पता होना आवश्यक है। इसलिए, इसका सटीक मापन जरूरी है। इंजन-उपयुक्त ऊष्मा गतिकी स्थितियों में LBV को निर्धारित करने के लिए कांस्टेंट वॉल्यूम मेथड (CVM) एकमात्र तकनीक है। पारंपरिक CVM में जली हुई गैस का द्रव्यमान अंश निकालने के लिए जो मॉडल प्रयोग में लाया जाता है, उसकी कमियों के कारण और फ्लेम स्ट्रेच के प्रभाव से LBV का सही निर्धारण नहीं हो पाता। समय के साथ बदलते हुए दबाव के माप के अतिरिक्त फ्लेम त्रिज्या का माप भी किया जाए तो CVM के द्वारा LBV का सटीक निर्धारण किया जा सकता है। उपरोक्त वक्तव्य वर्तमान रिसर्च में CVM की सटीकता और उसकी कमियों का अवलोकन करने के लिए प्रेरित करता है।

CVM के लिए एक गोलाकार कक्ष सबसे अच्छा विकल्प है, क्योंकि ऐसे कक्षों में फ्लेम पूरे दहन के दौरान गोलाकार रहती है। हालाँकि, इस प्रकार के कक्ष में दीवारों की वक्रता के कारण लेंस प्रभाव उत्पन्न हो सकता है, जिसके कारण सटीक फ्लेम त्रिज्या प्राप्त करने के लिए ऑप्टिकल सुधार की आवश्यकता होगी। गोलाकार पारदर्शी कक्ष बनाना भी मुश्किल है। फ्लैट ऑप्टिकल विंडो का प्रयोग इन मुश्किलों को दूर कर सकता है। गोलाकार कक्ष में फ्लैट ऑप्टिकल विंडो का प्रयोग फ्लेम त्रिज्या-समय डेटा की उपयोगी सीमा को प्रतिबंधित करता है। पूर्ण फ्लैट ऑप्टिकल विंडो के साथ बेलनाकार कक्ष एक अन्य विकल्प है, और इसे बनाना भी आसान है। इस प्रकार का दहन कक्ष सम्पूर्ण फ्लेम त्रिज्या की दृश्यता और कोशकीय प्रभाव को पता लगाने में सहायक होता है।

बेलनाकार कक्ष में फ्लेम, प्रसार की अवधि के दौरान गोलाकार नहीं रहती। अतः प्रयोग के दौरान बेलनाकार के आधार की ओर से मापी हुई त्रिज्या का उपयोग जली हुई गैस की मात्रा और फ्लेम की सतह का क्षेत्रफल निकालने के लिए नहीं किया जा सकता। वर्तमान कार्य में CVM का प्रयोग करके बेलनाकार कक्ष में LBV के सटीक मान को निर्धारित करने के लिए एक नई पद्धति का प्रस्ताव रखा गया है। कम्प्यूटेशनल फ्लूइड डायनामिक्स (CFD) का उपयोग करके बेलनाकार और गोलाकार कक्षों में कांस्टेंट वॉल्यूम दहन का विस्तृत संख्यात्मक सिमुलेशन किया गया है। CFD सिमुलेशन का उपयोग करके बेलनाकार कक्ष में दहन के लिए दो सामान्यीकृत संबंध विकसित किए गए हैं। बेलनाकार कक्ष (L/D =1) में दहन की सिमुलेशन द्वारा, फ्लेम की सामान्यीकृत त्रिज्या ($R_{f,endview}/R_c$) और जली हुई गैस की मात्रा

(V_b/V_t) के बीच एवं फ्लेम की सामान्यीकृत त्रिज्या और फ्लेम की सतह के क्षेत्रफल (A_f/A_t) के बीच जो संबंध निकाले गए हैं वे पूरी तरह से ज्यामिती पर आधारित हैं। अतः ये संबंध ईंधन-वायु मिश्रण और कक्ष के आकार पर निर्भर नही करते। इन संबंधों का उपयोग करके $R_{f,endview}$ के किसी भी मान के लिए, किसी भी आकार के बेलनाकार कक्ष में जली हुई गैस की मात्रा और फ्लेम की सतह के क्षेत्रफल को प्राप्त किया जा सकता है। तदोपरांत, जली हुई गैस की मात्रा, फ्लेम की सतह के क्षेत्रफल और दाब-समय ट्रेस का उपयोग करके, जली हुई गैस का द्रव्यमान अंश निकाले बिना, LBV का सटीक निर्धारण किया जा सकता है।

सबसे पहले, संख्यात्मक सिमुलेशन से प्राप्त किये गए दाब-समय ट्रेस और $R_{f,endview}$ का उपयोग करके CVM से LBV के मान निकाले गए हैं। बेलनाकार कक्ष में निकाले गए LBV के मान, गोलाकार कक्ष में निकाले गए मानों के बराबर है। इसके बाद, प्रस्तावित विधि का उपयोग करते हुए जो LBV के मान प्राप्त हुए हैं उनमें से फ्लेम स्ट्रेच के प्रभाव को दूर किया गया है। मिश्रण के दिए गए ताप और दाब (p, T) पर प्राप्त किये गए LBV के मान से, फ्लेम स्ट्रेच के प्रभाव को दूर करने के लिए अलग-अलग फ्लेम स्ट्रेच के मानों के साथ LBV के मानों की आवश्यकता होती है, जिससे LBV के मान को फ्लेम स्ट्रेच के न होने की स्थिति के लिए निकला जा सकता है। इस प्रकार से निकाले गए LBV के मान गोलाकार कक्ष में बिना फ्लेम स्ट्रेच के प्राप्त किये गए LBV के मानों के बराबर है।

प्रस्तावित की गयी पद्धति को मीथेन-वायु मिश्रण के प्रायोगिक आंकड़ों के लिए प्रदर्शित किया गया है। इस पद्धति का प्रयोग करने के लिए 10.86 लीटर का एक पारदर्शी बेलनाकार कक्ष बनाया गया है जिसे गर्म करने की भी व्यवस्था है। प्रयोग के दौरान प्राप्त किए गए दाब-समय ट्रेस, $R_{f,endview}$ और विकसित किए गए संबंधों का उपयोग करके, CVM से स्टोइकियोमेट्रिक मीथेन-वायु मिश्रण की LBV के मान प्राप्त किये गए हैं, और प्राप्त किये गए मान पहले से प्रकाशित किये गए मानो के साथ अच्छी तरह से सहमति में हैं। वर्तमान कार्य में फ्लेम स्ट्रेच-सुधार विधि का प्रयोग करते हुए मीथेन-वायु मिश्रण के लिए 2.5 bar तक के दाब और समतुल्य अनुपात 0.8 - 1.2 के लिए स्ट्रेच रहित LBV के मान भी प्राप्त किये गए हैं । इस प्रकार, प्रस्तावित पद्धति CVM की सभी कमियों को पूरी तरह से समाप्त कर देती है, जिससे यह LBV के सटीक निर्धारण के लिए एक अच्छी विधि बन जाती है।

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Nomenclature

Abbreviations

1 – D	One Dimensional
PLC	Power-law Correlation
EGR	Exhaust Gas Re-circulation
CPM	Constant Pressure Method
CVM	Constant Volume Method
LBV	Laminar Burning Velocity
HTDR	Hybrid ThermoDynamic-Radiation
CFD	Computational Fluid Dynamics
ASME	American Society of Mechanical Engineers
TOF	Theory of Failure
PID	Proportional Integral Derivative
CCS	Control Center Series
MIE	Minimum Ignition Energy
IGBT	Insulated-gate Bipolar Transistor
PISO	Pressure-implicit Splitting of Operators

Greek Letters

α	Temperature Exponent
β	Pressure Exponent
Φ	Equivalence Ratio
θ	Half Cone Angle
γ	Specific Heats Ratio
γ_u	Unburned Mixture Specific Heats Ratio
γ_b	Burned Gas Specific Heats Ratio
ρ_u	Unburned Mixture Density
ρ_b	Burned Mixture Density
σ_a	Axial Stress
σ_r	Radial Stress
σ_t	Tangential Stress

σ_{ys}	Yield Strength
$\sigma_{bending}$	Bending Strength
τ	Shear Stress
K	Flame Stretch Rate

Symbols

A_f	Flame Surface Area
A_t	Total Inner Surface Area
$D_{bolt\ circle}$	Bolt Circle Diameter
$D_{inner\ dia\ of\ groove}$	Inner Dia of Groove
$D_{i,\ inner\ flange}$	Inner Dia of Inner Flange
$D_{i,\ pipe}$	Inner Dia of Pipe
$D_{i,\ supporting\ flange}$	Inner Dia of Supporting Flange
$D_{i,\ outer\ flange}$	Inner Dia of Outer Flange
D_g	Dia of Fused Quartz Glass Exposed to Pressure
L	Litre
$\dot{m}$	Mass Flow Rate
m_u	Unburned Mixture Mass
p	Pressure
p_i	Initial Pressure
p_e	End Pressure/Maximum Pressure
R	Spherical Chamber Radius
R_c	Cylindrical Chamber Radius
R_f	Spherical Flame Radius
$R_{f,end-view}$	End-View Flame Radius
R_i	Inner Radius of Cylindrical Vessel
R_o	Outer Radius of Cylindrical Vessel
S_b	Stretched Flame Speed
S_b^0	Unstretched Flame Speed
S_u	Stretched Laminar Burning Velocity

S_u^0	Unstretched Laminar Burning Velocity
t	Time
T	Temperature
t_{cc}	Combustion Chamber Wall Thickness
t_{glass}	Fused Quartz Plate Thickness
T_i	Initial Temperature
$t_{inner\ flange}$	Inner Flange Thickness
$t_{outer\ flange}$	Outer Flange Thickness
U_g	Unburned Fuel-air Mixture Velocity
V_b	Burned Gas Volume
V_t	Combustion Chamber Total Volume
v_u	Unburned Mixture Specific Volume
x	Burned Gas Mass Fraction

Subscripts

b	Burned
i	Initial
u	Unburned