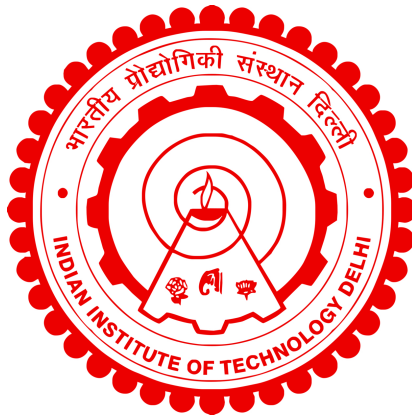


EXPERIMENTAL CHARACTERIZATION OF DIRECT INJECTION ETHANOL-GASOLINE SPRAYS IN A CONSTANT VOLUME CHAMBER

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**DEPARTMENT OF ENERGY SCIENCE AND
ENGINEERING**

INDIAN INSTITUTE OF TECHNOLOGY DELHI

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by

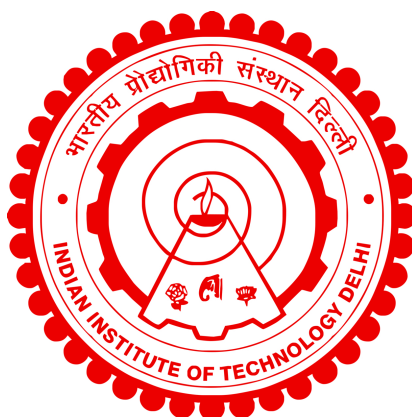
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Submitted

in the fulfillment of the requirements of the degree of Doctor of Philosophy

to the



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NOVEMBER 2024

*Dedicated to my mother, Late Smt. Chayya Gaur, my
father Sh. Anand Kumar Gaur, Geetanjali Nigam, and to
my Mother Land*

Certificate

This is to certify that the thesis entitled “**Experimental Characterization of Direct Injection Ethanol-Gasoline Sprays in a Constant Volume Chamber**” being submitted by **Anurag Gaur** to the **Indian Institute of Technology Delhi** for the award of the degree of **DOCTOR of PHILOSOPHY**, is a record of the bonafide research carried out by him which has been prepared under my supervision in conformity with the rules and regulations of the Indian Institute of Technology Delhi. He has fulfilled all requirements for the submission of this thesis, which has attained the standard required for a Ph.D degree of the Institute. The research reports and results presented in the thesis have not been submitted for any degree or diploma in any other university or Institute.

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“Failure will never overtake me if my determination to succeed is strong enough.”

Dr. A.P.J Abdul Kalam (Bharat Ratna)

(Former President and most decorated scientist of India)

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Abstract

The Direct Injection Spark Ignition (DISI) engine is a promising technology that aims to reduce emissions and improve fuel economy, offering a viable solution to current environmental concerns. The liquid fuel atomization and spray mixing process in a DISI engine are crucial stages before combustion, directly impacting subsequent events and engine performance. Fuel injection in a DISI engine typically operates at higher pressures. The atomization process in a DISI engine may occur due to non-flashing or flashing conditions based on the fuel temperature and chamber pressure. Therefore, it is vital to comprehend the physics involved in the atomization process from the start to the end of injection.

The study focuses on analyzing the spray formation in the near-nozzle region during the early and post-injection stages of development using a single-hole direct injection atomizer system with gasoline (G100) and ethanol-gasoline (E85) blended fuels. The research utilized a Galilean-type beam expander and an achromatic lens in conjunction with an LED light and a high-speed camera to observe and analyze the microscopic details of the spray in the near-nozzle region. Additionally, a laser-based technique was employed to investigate the macroscopic morphology of the spray and measure parameters such as liquid penetration, cone angle, and width.

Three different shapes, spheroids, cylindrical, and steeple, were visualized experimentally during the evolution of the fuel jet under different fuel injection and chamber pressures. A transition in shape from the steeple-to-spheroid shape was detected. It was observed that the velocity of the emerged jet is affected by its evolved shapes, attributing to differences in the initial breakup characteristics and shot-to-shot variation in the spray at a given condition. The velocity of the cylindrical-shaped jet was 14% and 42% higher than the steeple and spheroid-shaped jets, respectively.

The Rayleigh-Plesset equation describes the reason for an increase in the spheroidal-shaped jet velocity by 84% when the chamber pressure (P_{ch}) is reduced from 0.6 to 0.1 MPa. It was observed that the cylindrical and the steeple-shaped jets pertain to a higher tendency to atomize during the initial stage of evolution compared to the spheroidal jet. The average jet velocities and liquid penetrations in the near-nozzle region for E85 and G100 were estimated.

The post-injection liquid sheet formation near the nozzle exit was observed. Results show that the size of the liquid sheet depends on the liquid-to-gas density ratio (ρ). The size of the sheet for E85 fuel at ρ_{lg} of 2363 was found to be 6 mm, which was reduced by 75 % with a reduction in ρ_{lg} by 95 %. The chamber temperature increased from 303 K to 363 K, ρ_{lg} increased from 702 to 842, and a reduction in the liquid sheet was observed from 2.5 mm to 1.8 mm, respectively. The necking phenomenon of the liquid sheet was observed at the nozzle tip before the sheet detached and disintegrated into droplets. The necking length for the E85 was compared with gasoline fuel.

The transitional flashing jet acquired spheroid, cylindrical, and steeple shapes similar to non-flashing sprays. An orbicular-shaped structured jet was observed during flare flashing at 0.03 MPa chamber pressure and 363 K fuel temperature. It exhibits rapid axial momentum, resulting in a Reynolds number of 8.0×10^4 , which is 1.3 times and 2.15 times higher than the transitional and non-flashing, respectively. Additionally, it has an estimated nucleation rate of $3.22 \times 10^{-2} \text{ m}^{-3}\text{s}^{-1}$ using classical nucleation theory, which is 10 times higher than the transitional flashing, leading to improved atomization. However, spray collapse was observed under flare flashing with a reduction in P_{ch} , attributed to local condensation and subsequent pressure drop in core of the spray. Under flare flashing at a fuel temperature of 403 K, the Ohnesorge number is 2.95×10^{-3} , which is 0.8 times and 0.7 times lower than the fuel at 383 K and 363 K, respectively. The nucleation rate for flare flashing increases with higher fuel temperature, leading to improved atomization and a reduced likelihood of spray collapse. Post-injection spray structures in the near-nozzle show a transition from coarse to fine and dilute to densely populated with changes in the degree of superheating.

The macroscopic spray morphology for the flare flashing condition was compared using different imaging techniques including laser based diffused back illumination (DBI), LED based Mie scattered, and 1-Phase structured laser illumination planar imaging (1P-SLIPI), to demonstrate the advantage of SLIPI over conventional imaging to identify the dense and dilute region within the spray.

सार

डायरेक्ट इंजेक्शन स्पार्क इग्निशन (डीआईएसआई) इंजन एक आशाजनक तकनीक है जिसका उद्देश्य उत्सर्जन को कम करना और ईंधन अर्थव्यवस्था में सुधार करना है, जो वर्तमान पर्यावरणीय चिंताओं का एक व्यवहार्य समाधान पेश करता है। डीआईएसआई इंजन में तरल ईंधन परमाणुकरण और स्प्रे मिश्रण प्रक्रिया दहन से पहले महत्वपूर्ण चरण हैं, जो बाद की घटनाओं और इंजन के प्रदर्शन को सीधे प्रभावित करते हैं। डीआईएसआई इंजन में ईंधन इंजेक्शन आमतौर पर उच्च दबाव पर काम करता है। डीआईएसआई इंजन में परमाणुकरण प्रक्रिया ईंधन तापमान और चैम्बर दबाव के आधार पर गैर-प्लैशिंग या प्लैशिंग स्थितियों के कारण हो सकती है। इसलिए, इंजेक्शन की शुरुआत से अंत तक परमाणुकरण प्रक्रिया में शामिल भौतिकी को समझना महत्वपूर्ण है।

अध्ययन गैसोलीन (G100) और इथेनॉल-गैसोलीन (E85) मिश्रित ईंधन के साथ एकल-छेद प्रत्यक्ष इंजेक्शन एटमाइज़र प्रणाली का उपयोग करके विकास के प्रारंभिक और इंजेक्शन के बाद के चरणों के दौरान निकट-नोजल क्षेत्र में स्प्रे गठन का विश्लेषण करने पर केंद्रित है। अनुसंधान ने निकट-नोजल क्षेत्र में स्प्रे के सूक्ष्म विवरण का निरीक्षण और विश्लेषण करने के लिए एक एलईडी लाइट और एक उच्च गति वाले कैमरे के साथ गैलिलियन-प्रकार के बीम विस्तारक और एक अक्रोमेटिक लेंस का उपयोग किया। इसके अतिरिक्त, स्प्रे की मैक्रोस्कोपिक आकृति विज्ञान की जांच करने और तरल प्रवेश, शंकु कोण और चौड़ाई जैसे मापदंडों को मापने के लिए एक लेजर-आधारित तकनीक को नियोजित किया गया था।

विभिन्न ईंधन इंजेक्शन और चैम्बर दबावों के तहत ईंधन जेट के विकास के दौरान प्रयोगात्मक रूप से तीन अलग-अलग आकृतियों, गोलाकार, बेलनाकार और स्टीपल की कल्पना की गई थी। मीनार से गोलाकार आकार में परिवर्तन का पता चला। यह देखा गया कि उभरे हुए जेट का वेग उसके विकसित आकारों से प्रभावित होता है, जो प्रारंभिक ब्रेकअप विशेषताओं में अंतर और किसी निश्चित स्थिति में स्प्रे में शॉट-टू-शॉट भिन्नता के कारण होता है। बेलनाकार आकार के जेट का वेग स्टीपल और गोलाकार आकार के जेट की तुलना में क्रमशः 14% और 42% अधिक था।

रेले-प्लेसेट समीकरण गोलाकार आकार के जेट वेग में 84% की वृद्धि का कारण बताता है जब चैम्बर दबाव (P_{ch}) 0.6 से 0.1 एमपीए तक कम हो जाता है। यह देखा गया कि बेलनाकार और मीनार के आकार के जेट गोलाकार जेट की तुलना में विकास के प्रारंभिक चरण के दौरान परमाणु बनाने की उच्च प्रवृत्ति से संबंधित हैं। E85 और G100 के लिए निकट-नोजल क्षेत्र में औसत जेट वेग और तरल प्रवेश का अनुमान लगाया गया था।

प्रारंभिक चरण के दौरान जेट के टूटने की स्थिति का वर्णन करने के लिए उभरे हुए तरल जेटों की ओहनेसॉर्ज और रेनॉल्ड्स संख्या का अनुमान लगाया गया था। प्रारंभिक चरण के दौरान 2 एमपीए इंजेक्शन दबाव पर स्प्रे 0.6 MPa P_{ch} के तहत दूसरा हवा-प्रेरित ब्रेकअप दिखाता है। 0.03 और 0.05 MPa P_{ch} के तहत जेट के लिए दूसरी-पवन और परमाणुकरण ब्रेकअप के बीच एक संक्रमण। जेट 0.1 MPa P_{ch} के अंतर्गत परमाणुकरण विखंडन का अनुभव करता है। इंजेक्शन के दबाव और चैम्बर तापमान के प्रभाव का भी अध्ययन किया गया।

नोजल निकास के पास इंजेक्शन के बाद तरल शीट का निर्माण देखा गया। परिणाम बताते हैं कि तरल शीट का आकार तरल-से-गैस घनत्व अनुपात (ρ_{lg}) पर निर्भर करता है। 2363 के ρ_{lg} पर E85 ईंधन के लिए शीट का आकार 6 मिमी पाया गया, जिसे ρ_{lg} में 95% की कमी के साथ 75% कम किया गया। चैम्बर का तापमान 303 K से बढ़कर 363 K हो गया, ρ_{lg} 702 से बढ़कर 842 हो गया, और तरल शीट में क्रमशः 2.5 मिमी से 1.8 मिमी की कमी देखी गई। तरल शीट की नेकिंग घटना को शीट के अलग होने और बूंदों में विघटित होने से पहले नोजल टिप पर देखा गया था। E85 की नेकिंग लंबाई की तुलना गैसोलीन ईंधन से की गई थी।

संक्रमणकालीन फ्लैशिंग जेट ने गैर-फ्लैशिंग स्प्रे के समान गोलाकार, बेलनाकार और खड़ी आकृतियाँ प्राप्त कर लीं। 0.03 MPa P_{ch} और 363 K ईंधन तापमान पर फ्लेयर फ्लैशिंग के दौरान एक कक्षीय आकार का संरचित जेट देखा गया। यह तीव्र अक्षीय गति प्रदर्शित करता है, जिसके परिणामस्वरूप रेनॉल्ड्स संख्या 8.0×10^4 होती है, जो क्रमशः संक्रमणकालीन और गैर-फ्लैशिंग से 1.3 गुना और 2.15 गुना अधिक है। इसके अतिरिक्त, शास्त्रीय न्यूक्लियेशन सिद्धांत का उपयोग करते हुए इसकी अनुमानित न्यूक्लियेशन दर $3.22 \times 10^{-2} \text{ m}^{-3}\text{s}^{-1}$ है, जो संक्रमणकालीन फ्लैशिंग से 10 गुना अधिक है, जिससे परमाणुकरण में सुधार होता है। हालाँकि, P_{ch} में कमी के साथ फ्लेयर फ्लैशिंग के तहत स्प्रे का पतन देखा गया, जिसका कारण स्थानीय संक्षेपण और बाद में स्प्रे के मूल में दबाव में गिरावट थी। 403 K के ईंधन तापमान पर फ्लेयर फ्लैशिंग के तहत, ओहनेसॉर्ज संख्या 2.95×10^{-3} है, जो क्रमशः 383 K और 363 K पर ईंधन की तुलना में 0.8 गुना और 0.7 गुना कम है। उच्च ईंधन तापमान के साथ फ्लेयर फ्लैशिंग के लिए न्यूक्लियेशन दर बढ़ जाती है, जिससे परमाणुकरण में सुधार होता है और स्प्रे ढहने की संभावना कम हो जाती है। निकट-नोजल में इंजेक्शन के बाद की स्प्रे संरचनाएं सुपरहीटिंग की डिग्री में बदलाव के साथ मोटे से बारीक और पतले से घनी आबादी में संक्रमण दिखाती हैं।

फ्लेयर फ्लैशिंग स्थिति के लिए मैक्रोस्कोपिक स्प्रे आकृति विज्ञान की तुलना अलग-अलग इमेजिंग तकनीकों का उपयोग करके की गई थी, जिसमें लेजर-आधारित डिफ्यूज्ड बैक इल्यूमिनेशन (DBI),

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Symbols

Θ	Non-dimensional surface tension
θ	Spray cone angle
μ	Dynamic viscosity
ν	Kinematic viscosity
ρ_{lg}	Liquid-to-gas density ratio
ρ_g	Gas density
ρ_l	Liquid density
ρ_v	Vapor density
σ	Surface tension
c_p	Specific heat at constant pressure
d	Nozzle diameter
h_{lv}	Latent heat of vaporization
J_{CNT}	Nucleation rate
k_b	Boltzmann Constant
M	Molar mass
N_A	Avogadro number
P_{ch}	Chamber pressure
P_{inj}	Fuel injection pressure
P_{sat}	Saturation pressure
Re_l	Reynolds number (liquid)
R_p	Pressure ratio
ΔT	Degree of superheating/subcooling
T_{ch}	Chamber temperature
T_{fuel}	Fuel temperature
V_{jet}	Velocity of the jet in near-nozzle

We_l	Weber number (liquid)
We_g	Weber number (gas)
U	Jet velocity

Abbreviations

AEOI	After the end of injection
ASOI	After the start of injection
DBI	Diffused back illumination
DISI	Direct injection spark ignition
E85	85% by volume ethanol and 15% by volume gasoline
G100	Pure gasoline (commercial)
GDI	Gasoline direct injection
Ja	Jackob number
KH	Kelvin-Helmholtz
LDM	Long-distance microscope
Oh	Ohnesorge number
PAHs	Polycyclic aromatic hydrocarbons
PM	Particulate matter
RT	Rayleigh-Taylor
1P-SLIPI	1-Phase structured laser illumination planar imaging
SMD	Sauter mean diameter
UBHCs	Unburnt hydrocarbons