

SPRAY MODELLING FOR GASOLINE DIRECT INJECTION APPLICATIONS

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INDIAN INSTITUTE OF TECHNOLOGY DELHI
JANUARY 2025

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SPRAY MODELLING FOR GASOLINE DIRECT INJECTION APPLICATIONS

by

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Submitted

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

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

JANUARY 2025

Dedicated

To

My mother, Mrs. Yadamma Aisaboina, and

My father, Mr. Sudhakar Aisaboina

Certificate

This is to certify that the thesis entitled “**Spray Modelling for Gasoline Direct Injection Applications,**” being submitted by **A Akhil** 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 from 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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Acknowledgements

I express my profound gratitude to the fierce energies of Shiva and Shakti for empowering me with the inner strength I need to pursue my dreams confidently!

I want to express my sincere gratitude for the constant support, guidance, and invaluable feedback I received throughout my Ph.D. journey from my supervisor, Prof. Kaushik Saha. He has been incredibly kind and generous in sharing his extensive knowledge in the fields of Computational Fluid Dynamics (CFD) and fuel injection systems. The research discussions we had, along with our group members, greatly enhanced my learning experience and significantly improved my ability to think independently. Prof. Saha has always shown concern for my well-being and research progress. I will be forever grateful to him.

I express my sincere gratitude to the members of my research committee, Prof. K.A. Subramanian (Chairperson), Prof. Dibakar Rakshit (Internal Expert), and Prof. Krishnakant Agrawal (External Expert), for their constant feedback and encouragement throughout this journey.

I am grateful to Dr. Vipin Dhyani for his support and guidance during the early stages of my research at IIT Delhi. I am thankful to my research colleagues, Dr. Srijna Singh, Dr. Anurag Gaur, Dr. Akshey Marwaha, Mr. Arun RS, Mr. Rajneesh Kashyap, Mr. Santu Dolui, Mr. Venkata Koti, for their help and cooperation in many ways during my Ph.D. journey.

I thank PADUM: Hybrid High-Performance Computing Facility at IITD for providing computational resources. Without this cluster, it would not have been possible for me to run the high-fidelity simulations performed in this work. I want to thank Dr. Manish Agarwal for taking the time to help us install the CONVERGE CFD software in the IITD cluster.

I am thankful to Convergent Science India for providing a free CONVERGE CFD license during the final stages of my Ph.D., which helped me to run multiple simulations and finish my Ph.D. on time. I want to thank Mr. Mukul Biware from Convergent Science India for assisting in creating the stepped hole geometry.

I am deeply indebted to my parents (Mr. Sudhakar Ailaboina and Mrs. Yadamma Ailaboina) and my brother (Mr. Anirudh Ailaboina) for their unconditional love, care and support. I dedicate this work to my father, Mr. Sudhakar Ailaboina, and mother, Mrs. Yadamma Ailaboina. Without their support and encouragement, I would not have been able to dream of pursuing a Ph.D. Special thanks to my wife (Dr. Tejaswini Bachanaboina) for understanding my situation and constant support and encouragement while writing my thesis and during the final stages of my Ph.D. journey.

Finally, I want to express my sincere gratitude to my friends, teachers, and everyone who has believed in me. Your support has been invaluable, and the lessons I have learned from each person along my journey have shaped who I am today.

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Abstract

The gasoline direct injection (GDI) system is a promising technology that helps the engine to run at a higher compression ratio and achieve a higher volumetric efficiency compared with the port fuel injection (PFI) engines. The atomization of the fuel spray mainly influences the combustion performance of a GDI engine. GDI often operates at a higher injection pressure than PFI systems, which is believed to lead to better spray atomization. It implies that finer droplets lead to faster vaporization and better air-fuel mixing. In this work, an eight-holed counter bore GDI injector from Engine Combustion Network (ECN) called “Spray G” is considered. The simulations were carried out using the standard rate of injection (ROI) based Eulerian-Lagrangian approach, using the isooctane as the fuel. These simulations were carried out using the RNG $k-\varepsilon$ turbulence model. However, the other turbulence models, such as the standard $k-\varepsilon$ turbulence model and LES-based different sub-grid models, were also considered in this study under non-flashing conditions.

Firstly, numerical investigations were conducted under non-flashing operating conditions. It has been observed from the literature that the validation of Spray G is carried out mostly by varying the turbulence model constants and/or by an unusually wide spray cone angle. Most of the studies in the literature validated their model setups using the old spray penetration data from the ECN database. In recent years, the ECN database has provided new sets of penetration data which are deemed more reliable. Therefore, this study uses the latest data on spray penetrations from ECN for model validation and experimental findings on suction velocity and local droplet diameter. From the literature, it has been observed that validating these three parameters together is challenging. The validation studies were carried out by considering the KH-RT breakup length model. Several parametric studies were carried out by varying the KH model size constant (B_1) and the RT model breakup length constant (C_{bl}). Under non-flashing conditions, using the RNG $k-\varepsilon$ turbulence model, the following model constants were recommended: B_1 as 32 and C_{bl} as 16. The predicted results showed reasonable agreement with the experimental data in terms of spray penetrations, prediction of suction velocity at 15 mm below the injector tip, and prediction of local droplet diameter at 15 mm below the injector tip.

Flash-boiling is a non-equilibrium phenomenon often occurring in a GDI engine during part load and idle operating conditions. Engine computational fluid dynamics (CFD) deal with a range of length-scales and multiple sub-models, and hence, often simplified models with

reasonable assumptions are preferred to address rather complex phenomena. The literature review indicated the lack of a simplified engineering-level model to account for flashing sprays in engine CFD. To overcome this problem, a flash vaporization model based on the relevant non-dimensional numbers was developed and implemented in this study. Parametric studies were carried out to optimize the developed flash vaporization and breakup model constants under flash-boiling conditions. The results obtained from this parametric study were compared with the experimental data from ECN. It has been observed that the predicted results are within the range of the experimental observations in terms of spray penetration, spray width, and Sauter mean diameter (SMD).

Further, numerical studies were conducted to study the application of alternative fuels on a GDI injector under non-flashing and flashing conditions. Under non-flashing conditions, the blend of alternative fuels such as ethanol and methanol with isooctane has lower liquid penetration than the pure isooctane fuels spray. Numerical studies indicated that fuel properties such as the latent heat of vaporization and density were dominant. Additionally, on mixing of alcohol fuels with the isooctane, the charge cooling effect is observed through these studies. Local cooling of air-fuel mixtures by 30-40 K is observed when the alcohol content of the blend is increased. Furthermore, simulations were conducted under similar flash-boiling operating conditions, using ethanol and methanol as fuels, using the validated model setup of flash vaporization and modified breakup constants. Since ethanol and methanol's physical and saturation properties differ from the isooctane fuel, the fuel spray behaved differently. Compared with the experimental data, the predicted results of ethanol and methanol spray also achieved a reasonable agreement.

The developed flash vaporization model and the suggested breakup model constants were implemented in a GDI engine combustion under flashing conditions. These models were implemented using the CONVERGE user-defined functions (UDFs) so that the model constants and modelling approach would adapt based on the change in the surrounding conditions of the spray.

सार

गैसोलीन डायरेक्ट इंजेक्शन (GDI) प्रणाली एक आशाजनक तकनीक है जो इंजन को उच्च संपीड़न अनुपात पर चलने और पोर्ट फ्यूल इंजेक्शन (PFI) इंजन की तुलना में उच्च वॉल्यूमेट्रिक दक्षता हासिल करने में मदद करती है। ईंधन स्प्रे का परमाणुकरण मुख्य रूप से जीडीआई इंजन के दहन प्रदर्शन को प्रभावित करता है। जीडीआई अक्सर पीएफआई सिस्टम की तुलना में उच्च इंजेक्शन दबाव पर काम करता है, जिसके बारे में माना जाता है कि इससे बेहतर स्प्रे परमाणुकरण होता है। इसका तात्पर्य महीन बूंदों से है जिससे तेजी से वाष्पीकरण होगा और अंततः बेहतर वायु-ईंधन मिश्रण होगा। इस कार्य में, इंजन दहन नेटवर्क (ECN) से आठ छेद वाले काउंटर बोर जीडीआई इंजेक्टर जिसे "स्प्रे जी" कहा जाता है, को फ्लैशिंग और गैर-फ्लैशिंग स्थितियों के तहत माना जाता है। ईंधन के रूप में आइसोक्टेन का उपयोग करके, इंजेक्शन की मानक दर (ROI) आधारित यूलेरियन-लैंग्रेन्जियन दृष्टिकोण का उपयोग करके सिमुलेशन किए गए थे। ये सिमुलेशन RNG $k - \epsilon$ टर्बुलेंस मॉडल का उपयोग करके किए गए थे। हालाँकि, इस अध्ययन में गैर-फ्लैशिंग स्थितियों के तहत अन्य टर्बुलेंस मॉडल जैसे स्टैंडर्ड $k - \epsilon$ टर्बुलेंस मॉडल और एलईएस आधारित विभिन्न उप-ग्रिड मॉडल पर भी विचार किया गया था।

सबसे पहले, संख्यात्मक जांच गैर-फ्लैशिंग परिचालन स्थितियों के तहत की गई थी। साहित्य से यह देखा गया है कि, स्प्रे जी का सत्यापन ज्यादातर टर्बुलेंस मॉडल स्थिरांक को अलग करके और/या असामान्य रूप से व्यापक स्प्रे शंकु कोण द्वारा किया जाता है। साहित्य में अधिकांश अध्ययनों ने ईसीएन डेटाबेस से पुराने स्प्रे प्रवेश डेटा का उपयोग करके अपने मॉडल सेटअप को मान्य किया। हाल के वर्षों में ECN डेटाबेस मान्य डेटा के नए सेट प्रदान करता है जिन्हें अधिक विश्वसनीय माना जाता है। इसलिए, इस अध्ययन में, ईसीएन से स्प्रे प्रवेश पर नवीनतम डेटा का उपयोग सक्शन वेलोसिटी और स्थानीय ड्रॉपलेट डीएमटीर पर प्रयोगात्मक निष्कर्षों के साथ-साथ मॉडल सत्यापन के लिए किया जाता है। साहित्य से यह देखा गया है कि इन तीन मापदंडों को एक साथ मान्य करना चुनौतीपूर्ण है। सत्यापन अध्ययन KH-RT ब्रेकअप लंबाई मॉडल पर विचार करके किए गए थे। केएच मॉडल आकार स्थिरांक (B_1) और RT मॉडल ब्रेकअप लंबाई स्थिरांक (C_{bl}) को अलग-अलग करके कई पैरामीट्रिक अध्ययन किए गए। गैर-फ्लैशिंग स्थितियों के तहत, RNG $k - \epsilon$ टर्बुलेंस मॉडल का उपयोग करते हुए, निम्नलिखित मॉडल स्थिरांक की सिफारिश, B_1 को 32 और C_{bl} को 16 के रूप में की गई थी। पूर्वानुमानित परिणामों ने स्प्रे प्रवेश के संदर्भ में प्रयोगात्मक डेटा के साथ उचित सहमति दिखाई, इंजेक्टर टिप के नीचे 15 मिमी पर सक्शन वेलोसिटी की भविष्यवाणी, और इंजेक्टर टिप के नीचे 15 मिमी पर स्थानीय ड्रॉपलेट डीएमटीर की भविष्यवाणी की गई।

फ्लैश बोइलिंग एक गैर-संतुलन घटना है जो अक्सर जीडीआई इंजन में आंशिक लोड और निष्क्रिय परिचालन स्थितियों के दौरान होती है। इंजन कम्प्यूटेशनल फ्लुइड डायनेमिक्स (CFD) लेन्थ स्केल्स और कई उप-मॉडलों की एक श्रृंखला से निपटता है और इसलिए, अक्सर जटिल घटनाओं को संबोधित करने के लिए उचित मान्यताओं वाले सरलीकृत मॉडल को प्राथमिकता दी जाती है। साहित्य समीक्षा ने इंजन CFD में फ्लैशिंग स्प्रे के लिए एक सरलीकृत इंजीनियरिंग स्तर के मॉडल की कमी का संकेत दिया। इस समस्या को दूर करने के लिए, इस अध्ययन में प्रासंगिक गैर-आयामी संख्याओं पर आधारित एक फ्लैश वाष्पीकरण मॉडल विकसित और कार्यान्वित किया गया था। विकसित फ्लैश वाष्पीकरण मॉडल स्थिरांक के साथ-साथ फ्लैश उबलने की स्थिति के तहत ब्रेकअप मॉडल स्थिरांक को अनुकूलित करने के लिए पैरामीट्रिक अध्ययन किए गए थे। इस पैरामीट्रिक अध्ययन से प्राप्त परिणामों की तुलना ECN के प्रयोगात्मक डेटा से की गई। यह देखा गया है कि अनुमानित परिणाम स्प्रे प्रवेश, स्प्रे चौड़ाई और सॉटर माध्य व्यास (SMD) के संदर्भ में प्रयोगात्मक अवलोकनों की सीमा के भीतर हैं।

इसके अलावा, गैर-फ्लैशिंग और फ्लैशिंग स्थितियों के तहत GDI इंजेक्टर पर वैकल्पिक ईंधन के अनुप्रयोग का अध्ययन करने के लिए संख्यात्मक अध्ययन आयोजित किए गए थे। गैर-फ्लैशिंग परिस्थितियों में यह देखा गया है कि आइसोक्टेन के साथ इथेनॉल और मेथनॉल जैसे वैकल्पिक ईंधन के मिश्रण में शुद्ध आइसोक्टेन ईंधन स्प्रे की तुलना में कम तरल प्रवेश होता है। संख्यात्मक अध्ययनों से संकेत मिलता है कि लटेंट हीट ऑफ़ वपूरिज़िऑन और डेंसिटी जैसे ईंधन गुण प्रमुख थे। इसके अतिरिक्त, आइसोक्टेन के साथ अल्कोहल ईंधन के मिश्रण पर, इन अध्ययनों के माध्यम से चार्ज शीतलन प्रभाव देखा जाता है। जब मिश्रण में अल्कोहल की मात्रा बढ़ जाती है तो वायु-ईंधन मिश्रण का 30-40 K तक स्थानीय शीतलन देखा जाता है। इसके अलावा, फ्लैश वाष्पीकरण और संशोधित ब्रेकअप स्थिरांक के मान्य मॉडल सेटअप का उपयोग करते हुए, ईंधन के रूप में इथेनॉल और मेथनॉल का उपयोग करते हुए, समान फ्लैश बोइलिंग परिचालन स्थितियों के तहत सिमुलेशन आयोजित किए गए थे। चूंकि इथेनॉल और मेथनॉल के भौतिक और संतृप्ति गुण आइसोक्टेन ईंधन से भिन्न होते हैं, इसलिए ईंधन स्प्रे पूरी तरह से अलग व्यवहार करता है। प्रयोगात्मक डेटा की तुलना में, इथेनॉल और मेथनॉल स्प्रे के अनुमानित परिणामों ने भी एक उचित समझौता हासिल किया।

विकसित फ्लैश वाष्पीकरण मॉडल और सुझाए गए ब्रेकअप मॉडल स्थिरांक को फ्लैशिंग स्थितियों के तहत जीडीआई इंजन दहन में लागू किया गया था। इन मॉडलों को कन्वर्ज UDFs का उपयोग करके कार्यान्वित किया गया था, इस तरह से कि मॉडल स्थिरांक और मॉडलिंग दृष्टिकोण स्प्रे के आसपास की स्थितियों में परिवर्तन के आधार पर अनुकूलित हो जाएंगे।

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Nomenclature

Abbreviations			
		D	Mass diffusivity of liquid vapor
aTDC	After top dead center		
AFR	Air-fuel ratio	DBI	Diffused backlight imaging
AMR	Adaptive mesh refinement	DDM	Discrete droplet model
ANL	Argonne national laboratory	EPA	Environmental protection agency
B_0	KH breakup model size constant	ELSA	Eulerian-Lagrangian spray atomization
B_1	KH breakup model time constant	ECN	Engine combustion network
		EU	European union
bTDC	Before top dead center	FFV	Flex-fuel vehicle
BEVs	Battery electric vehicles	FHEVs	Full hybrid electric vehicles
C_{bl}	RT model breakup length constant	GCI	Grid convergence index
		GDI	Gasoline direct injection
$C_{\varepsilon 1}$	standard k - ε turbulence model constant	GWP	Global warming potential
		H_l	Latent heat of the liquid
C_τ	RT time constant	HC	Hydrocarbon
C_{RT}	RT size constant	HRR	Heat release rate
CFL	Courant – Friedrichs – Lewy	ICE	Internal combustion engine
		ICEVs	Internal combustion engine vehicles
CI	Compression ignition		
CVC	Constant volume chamber	IMEP	Indicated mean effective pressure
CFD	Computational fluid dynamics		

Ja	Jakob number	PHEVs	Plug-in hybrid electric
Ja_{ref}	Jakob number reference		vehicles
k	Turbulent kinetic energy, m^2/s^2	PISO	Pressure implicit with splitting of operators
KH	Kelvin – Helmholtz	QSMS	Quasi – simultaneous Mie – scattering and schlieren
L_b	Breakup length		
L/D	Length – to – diameter	Re	Reynolds number
LES	Large eddy simulation	r	Parent droplet radius, m
LES-DS	Large eddy simulation dynamic structure	r_c	Child droplet radius, m
LCA	Life-cycle analysis	R_p	Pressure ratio
LPL	Liquid penetration length	RNG	Re-normalization group
LPL	Liquid penetration length	ROI	Rate of injection
NITI	National institution for transforming India	RT	Rayleigh – Taylor
NEDC	New European driving cycle	RED	Renewable energy directive
NO_x	Oxides of nitrogen	RPM	Rotations per minute
ODE	Ordinary differential equation	Sc	Schmidt number
P_∞	Ambient pressure	Sh_d	Sherwood number
P_s	Saturation pressure	SMD	Sauter mean diameter
P_v	Partial vapor pressure	SI	Spark ignition
PFP	Peak firing pressure	SOI	Start of injection
PFI	Port fuel injection	T_f	Vapor film temperature
PM	Particulate matter	T_d	Droplet temperature
		T_b	Boiling temperature
		THC	Total hydrocarbons
		UBHC	Unburnt hydrocarbon

UDF	User defined function
URANS	Unsteady Reynolds-averaged Navier-Stokes
VOCs	Volatile organic compounds
VPL	Vapor penetration length
Y_1	Vapor mass fraction
Y_1^*	Vapor mass fraction at the drop surface

Greek

α_{spray}	User defined scaling factor
ε	Dissipation rate of turbulent kinetic energy, m^2/s^3
ρ	Density, kg/m^3
ρ_g	Gas density, kg/m^3
ρ_l	Liquid density, kg/m^3
μ_t	Turbulent viscosity
τ_{ij}	Reynolds stress
τ_{RT}	RT breakup time
Λ_{KH}	KH wavelength
Ω_{KH}	KH maximum growth rate
τ_{KH}	KH breakup time
Λ_{RT}	RT wavelength
Ω_{RT}	RT wavenumber