Energietechnik

Stephan Kruse

Soot Formation of Gasoline Surrogate Components in Laminar and Turbulent Flames

SHAKER
VERLAG

Soot Formation of Gasoline Surrogate Components in Laminar and Turbulent Flames

Rußbildung von Benzin-Surrogat-Komponenten in laminaren und turbulenten Flammen

Von der Fakultät für Maschinenwesen der Rheinisch-Westfälischen Technischen Hochschule Aachen zur Erlangung des akademischen Grades eines Doktors der Ingenieurwissenschaften genehmigte Dissertation

vorgelegt von

Stephan Kruse

Berichter: Universitätsprofessor Dr.-Ing. Heinz Günter Pitsch
Professor Bassam Dally, PhD

Tag der mündlichen Prüfung: 01.02.2019

Berichte aus der Energietechnik

Stephan Kruse

Soot Formation of Gasoline Surrogate Components in Laminar and Turbulent Flames

Shaker Verlag
Düren 2019

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at http://dnb.d-nb.de.

Zugl.: D 82 (Diss. RWTH Aachen University, 2019)

Printed in Germany.

ISBN 978-3-8440-6854-2
ISSN 0945-0726

Shaker Verlag GmbH • Am Langen Graben 15a • 52353 Düren
Phone: 0049/2421/99011-0 • Telefax: 0049/2421/99011-9
Internet: www.shaker.de • e-mail: info@shaker.de

Acknowledgements

The present thesis was completed during my work as a research assistant at the Institute for Combustion Technology (ITV), RWTH Aachen University. The research was performed as part of the Cluster of Excellence „Tailor made fuels from Biomass“, which is funded by the Excellence Initiative of the German federal state government to promote science and research at German universities.

First, I would like to thank my adviser Prof. Dr.-Ing. Heinz Pitsch for his continuous guidance, encouragement, and support that allowed me to develop and follow my research ideas and interests. Then, I would like to thank my second supervisor Prof. Bassam Dally for his valuable comments on my research and his hospitality during my research visit at the University of Adelaide. I am also grateful to Prof. Dr.-Ing. Reinhold Kneer for being the chair of the committee.

I would like to extend my gratitude to my present and former colleagues at the Institute for Combustion Technology for their advice and help. My sincere thanks go to Dr. Antonio Attili, Dr.-Ing. Joachim Beeckmann, Lukas Berger, Dr.-Ing. Liming Cai, Marco Davidovic, Dominik Denker, Bernhard Jochim, Konstantin Kleinheinz, Metin Korkmaz, Achim Wick for the inspiring discussions and the great time we had in the past years. I am also very grateful for the support I received from the design office, the electronic workshop, the mechanical workshop, and the administration of the ITV. Moreover, I would like to thank the undergraduate students that worked with me over the past six years. In particular, I am grateful to my student assistants Yannick Heynen and Moritz Zuschlag for their help within the last year. I am also very grateful to Prof. Mohy Mansour, Prof. Paul Medwell, and Prof. Emilien Varea for the unforgettable research visits and productive collaborations.

Finally, I wish to thank my parents, my sister, and my brother for all their encouragement for more than thirty years. I am most grateful to my girlfriend Veronica for her unlimited support and patience during my research career.

Zusammenfassung

Direkt-einspritzende (DI-) Ottomotoren bieten ein großes Potential hinsichtlich der Effizienzsteigerung, allerdings stellen hierbei die verschärften Rußemissionsgrenzwerte eine enorme Herausforderung dar. Um die Rußemissionen von DI-Ottomotoren zu minimieren, sind ein detailliertes Verständnis und genaue Modelle der Rußbildung von Benzinkraftstoffen essentiell. Gegenstand dieser Arbeit ist daher die grundlegende Untersuchung der Rußbildung von Benzinsurrogat-Komponenten.

In einer Gegenstromkonfiguration wurde der Rußvolumenbruch in Ethylen-, n-Heptan-, iso-Oktan- und Toluolflammen mittels Laser-induzierter Inkandeszenz (LII) gemessen. Um die Messgenauigkeit der LII-Technik in Gegenstromflammen zu erhöhen, wurde ein Verfahren entwickelt, das es ermöglicht, die Auswirkungen von lokalen Schwankungen der Laserenergiedichte signifikant zu reduzieren.

Die Rußvolumenbrüche wurden daraufhin im Gegenstrombrenner für verschiedene Streckungsraten und Mischungsbrüche experimentell bestimmt. Dabei weisen die einzelnen Kraftstoffe signifikante Unterschiede in den Sensitivitäten des Rußvolumenbruchs bezüglich der Streckungsrate und des stöchiometrischen Mischungsbruchs auf. Eindimensionale Simulationen zeigen, dass die Rußbildung in Ethylenflammen von verschiedenen Modellen sehr gut vorhersagt wird, während die berechneten Rußemissionen der Benzinkraftstoffkomponenten bei allen Modellen deutlich über den experimentellen Werten liegen. Analysen der Spezieskonzentrationen in einer iso-Oktan- und einer Ethylenflamme zeigen, dass die Konzentrationen der Rußvorläufer in den iso-Oktanflammen im Vergleich zu den Ethylenflammen erheblich erhöht sind und aus den Pyrolyseprodukten des Kraftstoffs stammen.

Schließlich wurde in einer turbulenten Toluolflamme mittels verschiedener Lasermesstechniken Rußvolumenbruch, Rußpartikelgröße, Temperatur und Reaktionszone simultan bestimmt. Kombinierte Statistiken der charakteristischen Ruß- und Flammengrößen zeigen, dass Ruß aufgrund differentieller Diffusion in Gebieten niedrigerer Temperatur auf der brennstoffreichen Seite des OH-Gebiets präsent ist. Das Eindringen von Ruß in das OH-Gebiet legt nahe, dass entgegen häufiger Annahme die Rußoxidationsraten begrenzt sind und Ruß beim Eintritt in das Reaktionsgebiet nicht unmittelbar oxidiert.

Abstract

Stringent emission regulations aim to restrict soot emissions by particle mass and particle number in the transport sector. Whilst the concept of direct-injection gasoline (GDI) engines is very promising with respect to efficiency, complying with the legislative soot emission limits is challenging for GDI-engines. A sufficient reduction of soot emissions in GDI engines requires a detailed understanding and accurate modeling of soot formation processes of gasoline fuels in engines. This study provides fundamental investigations of the soot formation process of common gasoline surrogate components.

First, soot volume fraction measurements in ethylene, n-heptane, iso-octane, and toluene counterflow flames were performed by means of laser-induced incandescence (LII). This study demonstrates that large gradients in temperature and local gas composition, which are inherently present in counterflow flames, induce substantial beam steering effects. An approach is developed to ensure accurate LII measurements based on tailoring the mean laser fluence. The collected LII signal in the counterflow flames is thus nearly independent of beam steering effects.

The soot volume fraction profiles in the counterflow flames were then determined for a wide range of strain rates and stoichiometric mixture fractions. Sensitivities of soot formation on strain rate and stoichiometric mixture fraction were determined for each fuel, which are found to be strongly fuel-dependent. Simulations of the flames reveal that applied models are capable of predicting the soot volume fraction with remarkable accuracy for ethylene. For the gasoline surrogate components, however, the overall soot volume fractions are overpredicted. A reaction pathway analysis suggests that, in these flames, more soot precursors are formed via the reaction pathways involving fuel pyrolysis products.

Finally, flame structure, local gas temperature, local soot volume fraction, and primary soot particle diameter were simultaneously detected by means of optical diagnostics in turbulent toluene flames. Joint statistics of flame and soot properties indicate that, due to differential diffusion of soot, high soot concentrations are present at conditions of low temperatures and low OH concentrations. In the soot oxidation region, the presence of large particles suggests that oxidation is not sufficiently fast to burn soot completely.

Publications

This thesis is mainly based on the following journal publications.

- S. Kruse, A. Wick, P. Medwell, A. Attili, J. Beeckmann, and H. Pitsch. Experimental and numerical study of soot formation in counterflow diffusion flames of gasoline surrogate components. Submitted to *Combustion and Flame*

- S. Kruse, P. Medwell, J. Beeckmann, and H. Pitsch. The significance of beam steering on laser-induced incandescence measurements in laminar counterflow flames. *Applied Physics B*, doi.org/10.1007/s00340-018-7072-0, 2018

- S. Kruse, J. Ye, Z. Sun, A. Attili, B. Dally, P. Medwell, and H. Pitsch. Experimental investigation of soot evolution in a turbulent non-premixed prevaporized toluene flame. *Proceedings of the Combustion Institute*, doi.org/10.1016/j.proci.2018.05.075, 2018

- S. Kruse, M. S. Mansour, A. M. Elbaz, E. Varea, G. Grünefeld, J. Beeckmann, and H. Pitsch. Evaluation of partially premixed turbulent flame stability from mixture fraction statistics in a slot burner. *Combustion Science and Technology*, doi:10.1080/00102202.2018.1452393, 2018

- S. Kruse, B. Kerschgens, L. Berger, E. Varea, and H. Pitsch. Experimental and numerical study of MILD combustion for gas turbine applications. *Applied Energy*, 148:456-465, 2015

Contents