DOE Awards $1/2 Million to ERC for HCCI Engine Optimization and Control

The U.S. Department of Energy has awarded $1/2 million to the ERC to develop methods to optimize and control homogeneous-charge compression ignition (HCCI) engines. The funding will cover three years at $500,000 per year beginning January 2002. Collaborators within the ERC on the project are Kevin Hoag and Professors Rolf Reitz, David Foster, and Chris Rutland, as well as Professor Dan Haworth from Pennsylvania State University.

HCCI offers the potential of nearly eliminating internal combustion nitrogen oxide and particulate emissions at reduced cost over compression ignition direct injection engines by controlling pollutant emission within the cylinder. For gasoline engines, HCCI can be used to extend the operating envelope of port-fuel injected and gasoline direct injection engines, with corresponding increases in fuel efficiency and reduced emissions. The major technical challenges of HCCI are controlling combustion phasing and reducing unburned hydrocarbon and carbon monoxide emissions.

The project study will include both experimental and theoretical tasks. Experiments will use fully-instrumented engines with a wide range of displacements and deactivation for flow control and modern fuel injection systems. Candidate sensors for engine control include crankshaft speed observers, spark plug ionization current and fiber optic detectors. Emissions diagnostics include engine-out fast NOx and HC instruments (cycle-resolved) and in-cylinder laser visualization. Modeling tools include multi-dimensional codes, with state-of-the-art large eddy simulation turbulent combustion models and CHEMKIN for detailed kinetics. Engine performance models include zero- and one-dimensional global models for control system development, and response surface method and genetic algorithm optimization techniques.

The work will be conducted in collaboration with DOE national laboratories at Sandia, Lawrence Livermore, and Los Alamos. A number of industries (level 1 supporters) who will supply 20 percent matching funds for this project include Caterpillar, Delphi, General Motors Research, Mercury Marine, Ricardo North America, and Yamaha. Providing additional technical advisors will be Cummins, Daimler Chrysler, Detroit Diesel, Ford Motor Company, and International (Navistar).
New Assistant Professors, Lester Su and Scott Sanders, Join Faculty

Lester Su has joined the ERC faculty as an assistant professor. A native of Racine, Wisconsin, Su received his B.A. in physics from the University of Chicago. He earned his PhD at the University of Michigan in aerospace engineering, did post doctoral work at the University of Texas, next worked as a research fellow at Stanford, and then spent a year in Washington, D.C. as a congressional science and engineering fellow through ASME.

Su's research is focused on laser diagnostic imaging of turbulent mixing and combustion. He is now setting up his lab in room 209 ERB and is seeking student help. According to Su, his work ties in with structure-based computation efforts, complementing Professor Rutland's work. He will also be collaborating with Professors Leslie Smith (Mechanical Engineering and Mathematics) and Ricardo Bonazzo (Engineering Physics). During the spring semester, Su will be teaching ME563, Intermediate Fluid Mechanics.

When he is not on campus, Su can sometimes be found on the ice, playing hockey with ME Professor Jeffrey Giacomin's team. Su is also an accomplished violinist and a marathon runner. But a happy event is competing for Su's primary attention: his upcoming marriage to a professor at Johns Hopkins University, Allison Okamura.

Scott Sanders, new assistant professor, has joined the ERC after recently completing his PhD at Stanford. His thesis was entitled “Diode Laser Sensors for Harsh Environments with Application to Pulse Detonation Engines.” Originally from Iola, Wisconsin, Sanders earned his B.S. in mechanical engineering from Valparaiso University in 1997 and his M.S. from Stanford in 1998.

Sanders will continue his research into optical diagnostics for combustion in his ERC lab. For the spring semester, he will be teaching ME 361, Thermodynamics.

Professor Rutland Involved in New DOE Diesel Aftertreatment Program

Professor Chris Rutland is part of a new DOE committee called CLEERS (Cross-Cut Lean Exhaust Emissions Reduction). He is a member of the CLEERS coordinating subcommittee whose other members are from General Motors, Detroit Diesel, Northwestern University, Oak Ridge National Laboratory, and the U.S. Department of Energy headquarters. The committee's goal is to promote development of performance models for emissions control components such as exhaust manifolds, catalytic reactors, and sensors; to provide a consistent framework
for sharing information and making timely informed choices among emissions control technologies; and to identify R & D needs and priorities and provide endorsements for critical projects.

The committee organizes and holds regular workshops, and is developing a web-based data base for distributing data and models relevant to diesel aftertreatment. The workshops are focused on promoting the development of improved computational tools for simulating realistic full-system performance of lean-burn engines and the associated emissions control systems.

Additional information can be found at the CLEERS website: http://www.CLEERS.org/.

Message from the Director, Prof. Reitz

As you may know, starting this fall, Pat Farrell was called upon to serve as the Associate Dean of Academic Affairs in the College of Engineering. As a result, Pat has decided to step down as ERC Director, and I have been chosen to take his place.

There have been several exciting new developments at the ERC this fall. Firstly, we have been joined by two new faculty members, Professors Lester Su and Scott Sanders (see elsewhere in this Newsletter for more about Lester and Scott). They are both experimentalists, and we are excited about the new technology and expertise that they bring to the ERC.

The ERC has also been the recipient of several new large grants. The first is a $500K grant from General Motors Research and Development for research in compression ignition for both gasoline and diesel fuels, fuel spray modeling studies, engine and exhaust aftertreatment system model development, and turbulence modeling, with emphasis on light duty automotive applications.

The second is a three-year, $500K/year project from the Office of Heavy Vehicle Transportation of the Department of Energy on Homogeneous Charge Compression Ignition (HCCI) engine optimization and control. This project includes additional matching funding from engine manufacturers and other related industries, and collaboration with government laboratories and with Prof. Dan Haworth at the Pennsylvania State University on the development and application of advanced turbulence models.

These two new projects continue the tradition of ERC research which is to respond to the challenges that face the engine industry. Meeting upcoming emissions mandates for 2007 and beyond will require exciting new engine design concepts and new understandings of engine phenomena. The ERC faculty continues to be committed to the development and application of new analysis and diagnostic tools for engines, and to the transfer of this technology to the engine industry. The challenges faced by the industry are too great to be solved by individuals. By sharing expertise and ideas, and through the efforts of the ERC's highly motivated and gifted students and staff, technological advancements continue to be made at the ERC in areas of societal and national need. This makes the ERC an exciting place to work!

I look forward to serving my term as the ERC Director, and I invite you to contact us or to visit when you are in Madison.

Rolf D. Reitz
Wisconsin Distinguished Professor
New Fall Students in the ERC

The following graduate students are new to the ERC for the 2001-2002 academic year:

**Indranil Brahma** is a PhD student of Professor Rutland. He received his MS degree in New Delhi, India, and is researching engine system integration.

PhD student **Alper Bulca** is also working with Professor Rutland on “Homogeneous Charge Compression Ignition with EGR.” He comes to the ERC from Cukurova University in Turkey.

**Jared Cromas** is working with Professor Ghandhi on his MS. He earned his BS degree from the University of Michigan, and his project is “Particulate Formation Mechanisms in a Direct-Injection Gasoline Engine.”

**Peter Eckert** is a special student working with Professor Reitz. He comes to us from the University of Hanover, Germany, and his project’s goal is to develop a computer model to predict engine knocking in a small-size gasoline engine.

MS student **Rahul Jhavar** is also working with Professor Rutland. He earned his bachelor’s degree in Bombay, India.

MS student **Scott Foes** is working with Professor Farrell on imaging of dense fuel sprays. He received his B.S. from North Central College in Naperville, Illinois.

**Eric Hruby** earned his BS in mechanical engineering from UW-Madison and is now pursuing his MS with Professor Reitz. His project is about HCCI combustion analysis (diesel/gasoline).

MS student **Harmit Juneja** is working with Professor Reitz on his project, “Optimization of Emission Models for Diesel Engines with High EGR.” He received his bachelor’s degree from Regional Engineering College, Jalandhar, India.

**Adam Klingbeil** received his BSME from UW-Madison and is now working with Professor Reitz on his MS. His research involves the optimization of a heavy duty diesel engine using multiple injections and EGR to simultaneously reduce emissions and fuel consumption.

Master’s student **Amol Kulkarni** is working with Professor Rutland. He received his undergraduate degree in May of 1999 from the Government College of Engineering, Shivaji University, Karad, India.

Another of Professor Reitz’s new students is **Yi (Louis) Liu**. He is most recently from Ohio State University and is pursuing his PhD degree on modeling of HSDI diesel engines.

**Soamesh Manalgiri** is working with Professor Rutland on his MS. He received his BS degree from Government College of Engineering, Pune, India.

Project Assistant **Amar Patel** is working with Professor Reitz on computer modeling of direct-injection compression ignition engines using KIVA3v. He did his undergraduate work at the Nirma Institute of Technology, India.

**Matthew Wiles** is working with Professor Ghandhi on an examination of the effects of turbulence on mixing in a DISI engine. Matt earned his bachelor’s degree from Virginia Polytechnic Institute.

**Adam Wise** is a MS student of Professor Moskwa.

New Graduate Student Fellowships Awarded

ERC faculty have selected outstanding students to receive 60 percent fellowships: Chol-Bum Kweon, Chevron; Mark Beckman, Ford; and Soochan Park, GM. Additionally, 10 percent bonus fellowship funding is awarded to Dave Wickman from Ford and to Dave Rothamer from GM. Karen Bottom holds an SAE Yanmar Fellowship.
U.S. Representative Baldwin Visits ERC

Professor Rolf Reitz showed U.S. Representative Tammy Baldwin the ERC labs on her visit to the UW College of Engineering on August 27.

ERC Offers New Short Courses, Workshop

A new course entitled “Automotive Engine Design” is scheduled for April 22-24 in Dearborn, Michigan. The three-day program is for working engineers as well as technicians and design drafters, and will provide an overview of internal combustion engine design and mechanical development, focusing on automotive gasoline and diesel engines. For more information, visit the course website at www.erc.wisc.edu/pdseminars/autodesign.html.

A course on “IC Engine Performance & Emission Development” is offered May 7-9 in Madison, Wisconsin, on the University of Wisconsin campus. The program is designed to provide an overview of internal combustion engine performance and development for fuel economy and emissions, emphasizing fundamental engineering principles and their application to engine performance development. Optional course paths will allow participants to focus their studies on either spark-ignition or diesel engines. For more information, see the website at www.erc.wisc.edu/pdseminars/engineperf.html.

A workshop on “Multi-Dimensional Combustion Modeling for IC Engines” will be held June 12-14. For information on this class and other offerings, please contact Kevin Hoag by e-mail, hoag@facstaff.wisc.edu, or telephone (608)263-1610. For regular updates on courses, visit the ERC’s webpage at www.erc.wisc.edu/seminar.html.

ERC to Host ILASS Annual Conference in May

The Institute for Liquid Atomization and Spray Systems (ILASS), North and South America, will hold its 15th annual Conference on Liquid Atomization and Spray Systems in Madison, Wisconsin, May 14-17, 2002. Information about the program and registration can be found on the ERC website at www.erc.wisc.edu/.

ILASS was established in 1986 as an outgrowth of the International Conference on Liquid Atomization and Spray Systems (ICLASS). ILASS members are industrialists, researchers, academics, and students engaged in professional activities connected with the spraying of liquids. Professor Reitz is the local arrangements chair for the event, which will be at Madison’s Concourse Hotel. He can be reached via e-mail at reitz@engr.wisc.edu.
**Faculty, Staff and Student News**

Professor Christopher Rutland has received two grants from the Department of Energy’s new Scientific Discovery through Advanced Computing (SciDAC) program. For the first project, entitled “Terascale High-Fidelity Simulations of Turbulent Combustion with Detailed Chemistry: Spray Simulations,” Rutland will serve as a co-primary investigator with colleagues at the University of Maryland and the University of Michigan. Rutland will receive $228,400 for the three-year grant to implement a “first principles” simulation of reacting spray physics on massively parallel computers to be used in the study of turbulent homogeneous combustion ignition. In the second project, “An Algorithmic and Software Framework for Applied Partial Differential Equations: Combustion Applications,” Rutland will collaborate with researchers at the Lawrence Livermore National Laboratory. Rutland’s share of the three-year grant is $300,000 and will focus on fundamental turbulent combustion studies of fuel-air mixture preparations using advanced large-scale simulation techniques.

**General Motors Gives Half Million Dollars to the ERC**

We are pleased to announce that the collaborative effort between General Motors and the Engine Research Center has been significantly enhanced by a gift of $500,000. The gift from GM will be used to support our research and development of programs in homogeneous charge compression ignition combustion, both for gasoline and diesel fuels, and continued research in sprays, turbulence and engine exhaust aftertreatment. There has been a long and fruitful collaboration between GM and the Engine Research Center, dating back to the 1950’s.

Ongoing discussions on how to improve this relationship between the two laboratories culminated in October with a one and one-half day visit to the ERC by General Motors R&D personnel, Hazem Ezzat, Roger Fruechte, Nuno Vaz, Paul Najt, Roger Krieger and Man-Feng Chang. At this meeting, Hazem Ezzat, director of the GM R&D Powertrain Systems Research Laboratory, announced that the outstanding record of excellent research contributions made by the ERC convinced GM that a closer interaction with the ERC would be beneficial to GM and that as a means of enhancing their interaction with the ERC and supporting our activities, they would offer this gift of $500,000. The faculty and staff of the ERC are excited about this opportunity to augment our research and technical collaboration with General Motors R&D.

Emeritus Professor Phil Meyers is a member of a national committee called CAFE (Corporate Average Fuel Economy) whose mission is to advise Congress on requirements for SUV’s mileage levels. Currently, auto manufacturers must meet standards of about 27 miles per gallon for cars and 20.5 for light trucks. A year ago, Congress asked the National Research Council to do a study specifically for sport utility vehicles, and Myers was appointed to the 13-member CAFE committee. A former ERC PhD student, John Johnson, is also on the committee. Their report is being released soon.

ERC alumnus Syed M. Shahed (MS’69, PhD’71) has been awarded a Distinguished Service Award by the UW College of Engineering. Shahed lives in Rancho Palos Verdes, California, and is Vice-President of Research and Development for Honeywell Turbocharging Systems. When he was a student at the UW, Shahed worked with former ERC faculty member, Henry Newhall.

In November, the ERC hosted a tour of the labs for undergraduate engineering students who were in town for the national Pi Tau Sigma student honor society convention. These were among the best mechanical engineering students from around the country.

With the ERC’s recommendation, the university has awarded the PhD posthumously to student Derek Galligan, who died last May of cancer. Derek spent three years working at the ERC for Professor Reitz. His thesis was the “Effect of Ignition and Combustion on Diesel Engine Emissions.” Funding for the degree conferral was provided by the Uyehara Emergency Graduate Student Fund. The Uyehara fund was established via an anonymous donation to the UW Foundation to financially aid graduate students in the event of an emergency during their time as a student.
ERC Meets at SAE Congress in Detroit March 3-7

* Sunday, March 3, noon, Multi-dimensional Engine Modeling Users Group Meeting, hosted by Cray, Inc. in association with ERC, Detroit Downtown Courtyard by Marriott Hotel

** Wednesday, March 6, the GM-sponsored T:25 breakfast for ERC faculty and students will be held from 7 a.m. to 10 a.m. at the atrium of the Downtown Courtyard Marriott Hotel.

ERC Publications

The following abstracts include papers to be presented at the 2002 SAE Congress as well as other published papers by faculty and staff of the ERC.


A quantitative study of diesel fuel injection was conducted to investigate minute differences in spray plume development from several unique injector tips. In this study, a set of six eight-hole injector tips was assessed to evaluate distinguishable spray characteristics. The tips have known variability in soot and NOX data during in-engine testing. A spray fixture was constructed with a cam-pressurized electronic unit injector and a 5.1L, nitrogen-pressurized spray chamber. Injection conditions such as injection timing and duration were experimentally controlled to replicate actual engine load conditions. A copper-vapor laser illuminated the fuel spray, and a high-speed digital camera was timed to capture the injection events. Digital analysis of the spray images produced quantified penetration length, cone angle, and two-dimensional area data as a function of crank angle. The first five observed spray images (up to a spray radius of approximately 6 cm) of each injection event are presented. Initial qualitative analysis of the spray images indicated clear and repeatable asymmetries, as well as plume development differences between the injector tips. These observations suggest that early penetration length measurements are linked to emissions trends. It is assumed that variations in spray shapes can be correlated to NOX and soot data. The level of these differences, however, is minute, suggesting that detailed characterization strategies must be implemented to detect the spray patterns that are most influential to engine emissions.

“Properties of Homogeneous Charge Compression Ignition (HCCI) Engine with n-Butane Fuel,” Minoru Iida, Motoaki Hayashi, Dave Foster, Jay Martin, Accepted for publication in ASME Journal for Gas Turbine and Power.

In this paper, some basic properties of homogeneous charge compression ignition operation are investigated. The HCCI operating range for a CFR engine was determined with n-butane as fuel. The minimum and maximum load was determined using criteria of covariance of indicated mean effective pressure and the derivative of in-cylinder pressure respectively. Exhaust emissions, particularly hydrocarbons, were measured by Fourier transform infrared spectrometer. The concentration of intermediate hydrocarbon species rapidly decreased as the magnitude of the heat release increased. Hydrocarbon emission at the maximum HCCI load mainly consists of the fuel itself, which is probably emitted from colder areas in the combustion chamber. The relation between IMEPCOV and ISFC is discussed.


In this paper, effect of intake air temperature, coolant temperature, and compression ratio on start of heat release (SOHR) in HCCI engines is investigated. The operational range with HCCI was determined experimentally using a CFR engine with n-butane as the fuel. In-cylinder pressure was processed to evaluate SOHR. The effect of intake air and coolant temperature on SOHR increases as engine speed increases. In order to gain more insight into the combustion phenomena SOHR
was calculated using the theory of Livengood-Wu and compared with the experimental data. Dependence of SOHR on the equivalence ratio shows good correspondence between experiment and calculation. On the contrary, dependence on the intake air temperature and compression ratio shows poorer correspondence with predictions, especially under low engine speed. We interpret this as an indication of the importance of the active intermediate species that remain in the combustion chamber.


A study was undertaken to study several diesel injector nozzles that produced different engine emissions performance. The standard nozzles were VCO type nozzles that were manufactured using two different techniques. The nozzles were otherwise identical in all respects. The injector used was a cam pressurized EUI. Fired experiments were conducted on a Detroit Diesel Series 50 engine. Optical access was obtained by inserting a sapphire window in place of one of the exhaust valves. Under high speed, high load, retarded injection timing conditions, it was discovered that one nozzle produced higher soot and lower NOx emissions than the other nozzle. Pressure and heat release data, along with high speed film images were obtained. It was discovered that the temperature and KL factor results from the 2-color optical pyrometry showed a significant difference between the nozzles. The nozzle that produced higher soot with lower NOx also produced significantly higher KL factors coupled with slightly higher late cycle temperatures. In addition, a separate experiment provided unfired high speed spray images via a pressurized spray chamber, and these results showed differences in spray penetration and hole-to-hole variation for the nozzles.

Modeling the Effects of Auxiliary Gas Injection for Late Cycle Oxygen Enrichment in Heavy Duty Diesel Engines, Daniel Mather, David Foster, University of Wisconsin – Madison, Ashok Chanda, Tom Vachon, Caterpillar, Doug Longman and Ramesh Poola, Argonne National Laboratories.

A multidimensional simulation of Auxiliary Gas Injection (AGI) for late cycle oxygen enrichment was exercised to assess the merits of AGI for reducing the emissions of soot from heavy-duty diesel engines while not adversely affecting the NO emissions of the engine. Here, AGI is the controlled enhancement of mixing within the diesel engine combustion chamber by high-speed jets of air or another gas. The engine simulated was a Caterpillar 3401 engine. For a particular operating condition of this engine, the simulated soot emissions of the engine were reduced by 80 % while not significantly affecting the engine-out NO emissions compared to the engine operating without AGI. The effects of AGI duration, timing, and orientation are studied to confirm the window of opportunity for realizing lower engine-out soot while not increasing engine out NO through controlled enhancement of in-cylinder mixing. These studies have shown that this window occurs during the late combustion cycle, from 20 to 60 crank angle degrees after top-dead-center. During this time, the combustion chamber temperatures are sufficiently high that soot oxidation increases in response in increased mixing, but the temperature is low enough that NO reactions are quenched. The effect of the oxygen composition of the injected air is studied for the range of compositions between 21 % and 30 % oxygen by volume. This is the range of oxygen enrichment that is practical to produce from an air separation membrane. Simulations showed that this level of oxygen enrichment is insufficient to provide an additional benefit by either increasing the level of soot oxidation or prolonging the window of opportunity for increasing soot oxidation through enhanced mixing.

“Comparison of HCCI Operating Ranges for Combinations of Intake Temperature, Engine Speed and Fuel Composition,” Tanet Aroonsrisopon, Takeshi Morikawa, Minoru Iida, and David Foster, Submitted to 2002 Future Car Congress.

A series of engine experiments have been performed to explore the impact intake temperature, engine speed and fuel composition on the HCCI operating range of a CFR engine. The experimental matrix covers a range of engine speeds 600 - 200 RPM), intake temperatures (300 K - 400 K), and four different fuels. Three of the fuels had different chemical composition but had equivalent research octane numbers of 91.8. The fourth fuel, a blend of primary reference fuels had a research octane number of 70.
The acceptable HCCI operating range of the engine was defined through two criteria; the rate of pressure rise needed to be less than 10 MPa per crank angle and the covariance of the indicated mean effective pressure needed to be less than 10 percent. Using these limits the HCCI operating range for the engine was evaluated for the experimental matrix. Data for emissions, and fuel consumption as well as in-cylinder pressure were recorded.

The HCCI operating range was broader for the lower octane fuel. Finally it is observed that the chemical composition of the fuel is important. With all other input parameters being equivalent, the three fuels with the same research octane number all exhibit different HCCI operating regimes.


To experimentally investigate evaporating sprays under conditions experienced in high speed direct-injection (HSDI) diesel engines, the exciplex LIF technique with the TMPD / naphthalene dopant system was applied in a combustion-type constant-volume spray chamber. The chamber allows spark ignition of a slightly rich C2H2-air mixture, and subsequent fuel injection into the high temperature and pressure products. A detailed set of calibration experiments has been performed in order to quantify the TMPD fluorescence signal. It has been demonstrated that the TMPD fluorescence intensity is directly proportional to concentration, is independent of the chamber pressure, and was not sensitive to quenching by either water vapor or carbon dioxide. Therefore, the temperature dependence of the TMPD fluorescence was the only correction factor required for quantitative measurements. Using a dual heated-jet experiment, the temperature dependence of TMPD fluorescence up to 1000 K was measured. The temperature field in the spray images was determined using a simple mixing model, and an iterative solution method was used to determine the concentration and temperature field including the additional effects of the laser sheet extinction and laser sheet profile variations. The integrated fuel vapor concentration compared favorably with the measured amount of injected fuel for times when all of the liquid fuel had evaporated. The data indicate that early in the injection event liquid and vapor coexist at the spray leading edge, however the liquid length reaches a terminal value and the vapor phase continues to penetrate. The vapor concentration past the intact liquid length has an equivalence ratio from 2 - 3, similar to previous research. At temperatures higher than 1000K, the exciplex technique was found to have limited application due to thermal decomposition.


Vapor concentration measurements were performed for two unit injectors typically found in small- and medium-bore applications under evaporating conditions similar to those experienced in Diesel engines. Ambient gas temperatures of 800 and 1000 K and an ambient density of 15 kg/m3 were investigated using a constant volume combustion-type spray chamber. The exciplex laser-induced fluorescence technique with MPD/ naphthalene doped into the fuel was used to quantitatively determine the vapor-phase concentration and liquid-phase extent. The vapor-phase concentration was quantified using a previously developed method that includes corrections for the temperature dependence of the TMPD fluorescence, laser sheet absorption, and the laser sheet intensity profile. The effect of increase ambient temperature (1000 vs. 800 K) was significant on intact liquid length, and on the spray-spreading angle in the early portion of the injection period. Distributions of the vapor concentration for the higher temperature showed a wider extent with higher equivalence ratios, and the edge of the jet had higher gradients. The effect of increase injection pressure (1500 vs. 900 bar peak) was minimal on intact liquid lengths and spray-spreading angle, but distributions of the vapor concentration showed faster fuel vaporization rates and larger spray head volumes. The effect of increase nozzle hole size (267 vs. 158 mm diameter) was to increase the intact liquid length, but minimally affected the spray-spreading angle, and distributions of the vapor concentration showed a wider extent with higher equivalence ratios and bigger overall spray sizes.
expansion stroke well past the end of the main heat release showed the continued presence of 3-pentanone in the end gas with an equivalence ratio near 0.4, suggesting the lean quenching of the flame. Under all operating conditions there was a weak correlation between the fuel distribution near the spark gap at the time of ignition and the combustion performance on a cycle-by-cycle basis.


The noise characteristics of four camera systems representative of those typically used for laser-imaging experiments (a back-illuminated slow-scan camera, a frame-straddling slow-scan camera, an intensified slow-scan camera and an intensified video-rate camera) were investigated, and the results are presented as a function of the signal level and illumination level. These results provide the maximum possible signal-to-noise ratio for laser-imaging experiments, and represent the limit of quantitative signal interpretation. A calibration strategy for engine data that limits the uncertainties associated with thermodynamic and optical correction was presented and applied to engine data acquired with two of the camera systems. When a rigorous analysis of the signal is performed it is seen that shot noise limits the quantitative interpretation of the data for most typical laser-imaging experiments, and obviates the use of single-pixel data.


Planar laser-induced fluorescence of 3-pentanone doped into the fuel (iso-octane) and OH which is present in the combustion products has been performed in an optically accessible direct-injection spark-ignition (DISI) engine under stratified operating conditions. A wall-guided, swirl-based combustion chamber was utilized, and experiments were performed for light load, where the fuel-air equivalence ratio was 0.3, and high load conditions, with an equivalence ratio of 0.7, at speeds of 600 and 1200 rpm. The 3-pentanone images were calibrated through the use of a premixed charge condition of known equivalence ratio, with corrections applied for number density changes due to combustion. At the light load condition combustion of the highly stratified fuel cloud was directly measured for the first time. The equivalence ratio of the mixture at the flame front was found to be in the range from 0.5 - 0.8 for optimized combustion conditions in this engine. Large gradients were observed in the fuel distribution throughout combustion. Images acquired in the expansion stroke well past the end of the main heat release showed the continued presence of 3-pentanone in the end gas with an equivalence ratio near 0.4, suggesting the lean quenching of the flame. Under all operating conditions there was a weak correlation between the fuel distribution near the spark gap at the time of ignition and the combustion performance on a cycle-by-cycle basis.


The effects of augmented mixing through the use of an auxiliary gas injection (AGI) were investigated in a direct-injection gasoline engine operated at a 22:1 overall air-fuel ratio, but with retarded injection timing such that the combustion was occurring in a locally rich mixture as evident by the elevated CO emissions. Two AGI gas compositions, nitrogen and air, were utilized, the gas supply temperature was ambient, and a wide range of AGI timings were investigated. The injected mass was less than 10% of the total chamber mass. The injection of nitrogen during the latter portion of the heat release phase resulted in a 25% reduction in the CO emissions. This reduction is considered to be the result of the increased mixing rate of the rich combustion products with the available excess air during a time when the temperatures are high enough to promote rapid oxidation. This CO reduction was achieved despite the fact that the injected gas had a low temperature and was inert, both attributes should result in reduced oxidation rates. The effect of temperature and composition were observed by a significant reduction in the NOx emissions at the same conditions, confirming that the AGI orientation was effecting changes in the high temperature in-cylinder processes. At the same conditions air AGI (i.e., an oxidizing gas) produced a more significant CO reduction, and the oxygen content counteracted the low temperature to cause no change in the NOx emissions. These findings suggest that a lack of late-cycle mixing limits the emissions potential of current direct-injection engines.
An abrupt increase in tangential velocities near the chamber wall suggests that the re-circulation of surrounding gas is accelerated by the wall impingement, both for non-evaporating and evaporating sprays. The total transferred energies of laterally entrained gas by the single-hole injection sprays seem to be larger than those of six-hole injection sprays due to the higher positive normal velocities. The total transferred energies near 1100 K seem to be much larger than those of 293 K mainly due to the much higher enthalpy of entrained gas near 1100 K.


Four techniques were investigated for the characterization and quantification of fuel films in the intake port in a small four-stroke, air-cooled utility engine modified to use a fuel injector mounted in the place of the carburetor float bowl: step-fueling with constant air flow, step-throttle with constant fuel flow; skip-injection, and stop-injection tests. In the first two tests the exhaust air-fuel (A/F) ratio was measured with a fast-response universal exhaust gas oxygen (UEGO) sensor, while a fast flame ionization detector (FFID) was used in the latter two test methods. The engine was fueled with indolene, iso-octane, and propane to investigate and separate combustion and oil absorption/desorption from fuel film effects. The results indicate that the air flow through the intake port had the largest impact on the fuel film dynamics. Step-fueling tests showed only a short (less than 5 engine cycles) period during which the inducted A/F differed from the delivered A/F, whereas step-throttle tests showed a more pronounced A/F excursion that persisted for close to 20 engine cycles. The skip- and stop-injection tests indicated that vaporization from the fuel film contributed approximately 30% of the fuel inducted per cycle, regardless of load or the liquid fuel type. The overall film mass was found to be directly proportional to engine load (throttle position).


Airflow characteristics surrounding evaporating transient diesel sprays inside a constant volume chamber under temperatures around 1100 K were investigated using a six-hole injector and a single-hole injector. Particle Image Velocimetry (PIV) was used to measure the gas velocities surrounding a spray plume as a function of space and time.

A conical control surface surrounding the spray plume was chosen as a representative side entrainment surface. The positive normal velocities across the control surface of single-hole injection sprays were higher than those of six-hole injection sprays. The positive velocities tangential to the control surface of single-hole injection sprays were lower than those of six-hole injection sprays. An abrupt increase in tangential velocities near the chamber wall suggests that the re-circulation of surrounding gas is accelerated by the wall impingement, both for non-evaporating and evaporating sprays. The total transferred energies of laterally entrained gas by the single-hole injection sprays seem to be larger than those of six-hole injection sprays due to the higher positive normal velocities. The total transferred energies near 1100 K seem to be much larger than those of 293 K mainly due to the much higher enthalpy of entrained gas near 1100 K.


A micro-genetic algorithm ((GA) optimization method was applied to a heavy-duty, direct-injected diesel engine via an automated test bed system. The goal of this application was to demonstrate the feasibility and advantages of automated optimization experiments. With the genetic algorithm, no user input was required other than the factors of interest and their allowable ranges. This means that once the routine was initiated, it was essentially run undisturbed until a preset objective level was reached or a preset number of generations had been run. The automated (GA) was successfully demonstrated at all points of the six-mode transient cycle simulation, excluding idle. To accomplish the automated experiments, an automated testing system was developed around a Caterpillar single-cylinder diesel engine. An exhaust gas re-circulation (EGR) pumping system was installed along with analog and/or serial communication to and from the pump drive, the gaseous emissions analyzers, the intake and exhaust pressure controllers, the electronic unit injector (EUI) fuel injection system, and the AVL dynamic particulate analyzer that was used for online soot measurement. Customized software was also developed to run the optimization routine and interface with the (GA) code, the laboratory devices, and the engine. For comparison of optimization methods, a response surface method (RSM) was also performed at the high speed (1737 rev/min), medium load (57% max.) Mode 5. Interestingly, at this mode both the RSM and the (GA) located optima that had similar parameter values. In addition, at these optimum points, the engine was able to meet the 2002/2004 regulated emissions levels using the standard EUI and single injections.
A computational optimization study was performed for direct-injection diesel engine using a recently developed 1-D-KIVA3v-GA (1-Dimensional-KIVA3v-Genetic Algorithm) computer code. The 1-D-KIVA3v-GA code performs a full engine cycle simulation within the framework of a genetic algorithm (GA) code. Design fitness is determined using a 1-D (one-dimensional) gas dynamics code for the simulation of the gas exchange process, and the KIVA3v code for three-dimensional simulations of spray, combustion and emissions formation. The 1-D-KIVA3v-GA methodology was used to simultaneously investigate the effect of eight engine input parameters on emissions and performance for four cases, which includes high-speed high-load, high-speed low-load, low-speed high-load and low-speed low-load cases. The input parameters explored includes the start of injection (SOI) timing, injection duration, exhaust gas re-circulation (EGR), split injection rate shape, boost pressure, and finally the gas swirl and tumble ratios at intake valve closure. The predicted optimal results reduced the engine-out emissions along with a reduction of the specific fuel consumption compared to the baseline case. It was observed that the effect of the flow field (i.e., swirl and tumble ratios) at IVC on engine-out emissions was predominant only for the high-speed low-load case. Taking this in account, and with the idea of matching swirl and tumble ratios at IVC with the predicted optimal values of swirl and tumble ratios, a detailed flow analysis using VECTIS (a computational fluid dynamics code developed by Ricardo Software). Six different intake valve lift profiles were analyzed to obtain different flow fields at IVC. These profiles include cases with early and late intake valve closing as well as intake valve lift profiles with reduced maximum valve lift. The exhaust valve lift profile was kept common for all the six cases. VECTIS simulated the intake process (i.e., from intake valve open to intake valve closure) in the engine. The values of the swirl and tumble from the flow field obtained at intake valve closure (IVC) were analyzed for all the six intake valve lift profiles. Although it was not possible to generate the exact value of swirl and tumble ratios at IVC from the VECTIS result as predicted by the optimal design, nevertheless, the understanding generated for the effects of the different lift profiles on fluid flow parameters provides an important insight about the effect of different intake valve lift profiles on flow field development in the International (Navistar) 7.3 L diesel engine.


Models were developed to describe the vaporization of well-mixed wall films of multi-component engine fuels based on continuous thermodynamics, and applied for describing multi-component fuel spray-wall interactions. All the models were implemented into the KIVA3V-Release 2.0 code. Validation calculations were conducted for pulsed injection cases and compared with experimental wall film thickness data under different air fuel ratio and inflow conditions in an inclined pipe, which simulates an intake port of port fuel injection engines. For comparison, calculations with single-component iso-octane fuel were also conducted. The influence of wall temperature, inflow air velocity and injection angle on the wall film characteristics was studied. The results show that the multi-component fuel film is composed of increasingly heavy species as the vaporization proceeds.

The fuel film structure which results from the spray-pipe-wall interaction is significantly different from that resulting from spray-plane-wall interaction. An increase in the wall temperature significantly decreases both the film thickness and the film area. The injection angle significantly changes the wall film structure. Although the inflow velocity enhances the fuel vaporization rate, it has a relatively small effect on the fuel film movement.


A direct injection-gasoline (DI-G) system was applied to a heavy-duty diesel-type engine to study the effects of charge stratification on the performance of
premixed compression ignited combustion. The effects of the fuel injection parameters on combustion phasing were of primary interest. The simultaneous effects of the fuel stratification on Unburned Hydrocarbon (UHC), Oxides of Nitrogen (NOx), Carbon Monoxide (CO), and smoke emissions were also measured. Engine tests were conducted with altered injection parameters covering the entire load range of normally aspirated Homogeneous Charge Compression Ignited (HCCI) combustion. Combustion phasing tests were also conducted at several engine speeds to evaluate its effects on a fuel stratification strategy.


The causes of Unburned Hydrocarbon (UHC) emissions from a premixed compression ignited engine were investigated for both homogeneous and stratified charge conditions. A fast response Flame Ionization Detector (fast FID) was used to provide cycle-resolved UHC exhaust emission measurements. These fast FID UHC measurements were coupled with numerical flow simulation results to provide quantitative and qualitative insight into the sources of UHC emissions. The combined results were used to evaluate the effects of engine load, local gas temperatures, fuel stratification, and crevice quenching on UHC emissions.


Managing the injection rate profile is a powerful tool to control engine performance and emission levels. In particular, Common Rail (C.R.) injection systems allow an almost completely flexible fuel injection event in DI-diesel engines by permitting a free mapping of the start of injection, injection pressure, rate of injection and, in the near future, multiple injections. This research deals with the development of a network-based numerical tool for understanding operating condition limits of the Common Rail injector.

The models simulate the electro-fluid-mechanical behavior of the injector accounting for cavitation in the nozzle holes. Validation against experiments has been performed. The model has been used to provide insight into the operating conditions of the injector and in order to highlight the application to injection system design.


Cycle-resolved analysis of velocity data obtained in the re-entrant bowl of a high-speed, direct-injection diesel engine, demonstrates an unambiguous, approximately 100% increase in late-cycle turbulence levels over the levels measured during motored operation. RNG k-ε turbulence modeling, as implemented in KIVA-3V, does not capture this increased turbulence. The formation of an unstable radial profile of angular momentum, characterized by a negative radial gradient, is identified as the likely dominant source of the increased turbulence. Buoyant production is also found to be a likely source of enhanced radial velocity fluctuations between approximately 10 and 20 CAD. Finally, combustion induced gas expansion is found to produce a brief increase in turbulence near the time of the premixed burn. Burnout of the soot particles formed earlier in the combustion process.


In-cylinder fluid velocity is measured in an optically accessible, fired HSDI engine at idle. The velocity field is also calculated, including the full induction stroke, using multi-dimensional fluid dynamics and combustion simulation models. A detailed comparison between the measured and calculated velocities is performed to validate the computed results and to gain a physical understanding of the flow evolution. Motored measurements are also presented, to clarify the effects of the fuel injection process and combustion on the velocity field evolution. Mean in-cylinder angular momentum (swirl ratio) is well predicted, as are mean flow structures. The mean flow modification by fuel
injection and combustion is well captured. Substantial changes in the tangential velocity near the spray path are observed during the fuel injection event and, after combustion, a radial profile of the mean tangential velocity that favors turbulence production is developed within the bowl. RMS fluctuations show significant deviations between measurements and predictions over some portions of the cycle. Significant increases in measured fluctuations in the tangential component near the fuel spray path at start of injection (SOI), and in both the radial and tangential components within the bowl after combustion are absent from the model predictions. Measured fluctuations are anisotropic, and suggest turbulence production enhancing the tangential fluctuations near SOI, and enhancing the radial fluctuations after combustion.


Detailed chemical kinetics was implemented into an engine CFD code to study the combustion process in Homogeneous Charge Compression Ignition (HCCI) engines. The CHEMKIN code was implemented into KIVA-3V such that the chemistry and flow solutions were coupled. Effects of turbulent mixing on the reaction rates were also considered. The model was validated using experimental data from a direct-injection Caterpillar engine operated in the HCCI mode using gasoline. The results show that good levels of agreement were obtained using the present KIVA/CHEMKIN model for a wide range of engine conditions including various injection timings, engine speeds, and loads. It was found that the effects of turbulent mixing on the reaction rates needed to be considered to correctly simulate the combustion phasing. It was also found that the presence of residual radicals could enhance the mixture reactivity and hence shorten the ignition delay time. The NOx emissions were found to increase as the injection timing was retarded, in agreement with experimental results.


To overcome the trade-off between NOx and particulate emissions for future diesel vehicles and engines it is necessary to seek methods to lower pollutant emissions. The desired simultaneous improvement in fuel efficiency for future DI diesels is also a difficult challenge due to the combustion modifications that will be required to meet the exhaust emission mandates. This study demonstrates the emission reduction capability of EGR and other parameters on a High Speed Direct Injection (HSDI) diesel engine equipped with a common rail injection system using an RSM optimization method. Engine testing was done at 1757 rev/min, 45% load. The variables used in the optimization process included injection pressure, boost pressure, injection timing, and EGR rate. RSM optimization led engine operating parameters to reach a low-temperature and premixed combustion regime called the MK combustion region, and resulted in simultaneous reductions in NOx and particulate emissions without sacrificing fuel efficiency. It was shown that RSM optimization is an effective and powerful tool for realizing the full advantages of the combined effects of combustion control techniques by optimizing their parameters. It was also shown that through a close observation of optimization processes, a more thorough understanding of HSDI diesel combustion can be provided.


Fluid motion within the cylinder of a high-speed, direct-injection diesel engine influences the entire combustion process, from the initial fuel preparation prior to ignition to the late-cycle burn-out of unburned fuel and particulates. Multi-dimensional models are increasingly being used in the design and optimization of these engines. The ability of these models to accurately predict the in-cylinder flow structures and turbulence has yet to be proven, however, particularly under fired engine operation. In this paper, a comparison of experimental and predicted flow velocities, both before and after combustion, is...
presented. Experimental and predicted cylinder pressure and heat release are also compared. The engine geometry employed has geometric characteristics typical of modern light-duty diesels targeted for automotive applications, i.e.: four-valves; a central, vertical injector; a concentric, re-entrant bowl; and common-rail fuel injection equipment. The measurements are compared with the results of computations using STAR-CD and KIVA-3V, for the induction stroke and the compression/expansion strokes, respectively. All results reported here were obtained at an idle condition, characterized by a speed of 900 rpm and a gross IMEP of 1.2 bar. Cylinder pressure and heat-release are found to compare favorably between the experiment and the model predictions, although the predicted mass of fuel consumed in the premixed burn exceeds the measured mass burned. Similarly, the predicted in-cylinder angular momentum, obtained from a full induction stroke calculation, is found to agree to within 5% of the measured value. Just prior to the start of combustion, both modeled and experimental swirl velocity profiles are similar to solid-body fluid rotation. However, the model predicts significantly greater axial stratification of mean angular momentum than is observed experimentally. The r-z-plane mean-flow structure within the bowl is dominated by a single large-scale vortex. The location and speed of rotation of this vortex are well predicted by the model. Although RMS velocity fluctuations deep in the bowl are well-predicted at this time, larger fluctuations than the model predicts are observed experimentally near the top of the cylinder. These larger fluctuations are notably anisotropic, with the tangential component exceeding the radial component. After combustion, the axial distribution of mean angular momentum agrees more closely between model predictions and measurements. Large-scale, rotating structures in the r-z-plane, not present under motored engine operation, are also observed in both the measured and the predicted results. In contrast to the pre-combustion radial profile of tangential velocity, the post-combustion profile resembles that of a free-vortex, with the largest tangential velocities found at the inner radii. This type of profile suggests a source of turbulence production not found prior to combustion. At this time, the predicted RMS fluctuating velocities are considerably less than the measured fluctuations throughout the bowl. Measured fluctuations are again found to be anisotropic, although the radial fluctuations now exceed the tangential fluctuations.