Energy & Automotive Research Laboratory

MICHIGAN STATE UNIVERSITY
Creating Sustainable Energy Solutions

ON THE COVER: A prototype cylinder head featuring fast electric cam phasing, DI fuel injection, and multi-step lift. The system can transition from SI to HCCI mode and back in less than a dozen cycles. The assembly was designed and constructed in a cooperative effort between Chrysler, Delphi, and MSU researchers.
Teams of researchers at MSU are developing specifically formulated renewable fuels in tandem with specially designed engines — a distinctive, integrated approach that could drive the next automotive revolution.

Transportation accounts for two-thirds of oil consumption in the United States and one-third of all the energy used in the country. The critical need to reduce the nation’s dependence on oil imports, combined with today’s use of the same efficiency-limiting combustion system that powered the first automobiles more than 100 years ago, presents a significant challenge and opportunity. With deeply rooted expertise in agriculture, plant science, and engineering, MSU is ideally positioned to meet that opportunity.

The university has invested in an interdisciplinary academic community that is focused on automotive research and fuels in partnership with government and industry. In addition, MSU has developed an infrastructure that supports the study of vehicle engine efficiency, alternative energy, and emission reduction, with much of the research based in the Energy and Automotive Research Laboratories, a dynamic 40,000-square-foot research complex on the MSU campus.

Teams at the Energy and Automotive Research Laboratories also are developing methods to produce lighter, stronger parts that cut manufacturing costs and increase gas mileage and ways to convert waste vehicle exhaust into electricity to increase fuel economy.

MSU is home to one of the most advanced thermoelectric power generation research groups in the world. Part of the university’s automotive research involves recovering waste heat from diesel engines that is then used to extract energy to help power the vehicle. In addition to fuel economy improvements while traveling over the road, a TEG can also function as an auxiliary power unit while the vehicle is stationary, to reduce engine created noise and engine idle time for an additional fuel savings. Automobile companies are also turning to MSU’s hybrid vehicles team, which translates research conducted at the university for application to auto components to maximize the efficiency and affordability of hybrid models. MSU’s collaborative automotive and fuels research holds promise to reduce automobile emissions and improve the economic outlook for Michigan.

The impact of new engine concepts and advanced hybrid powertrain designs can improve the efficiency of a vehicle from 20 to 50 percent. If technology is implemented to achieve a 20 percent increase in efficiency for all automobiles and trucks in the U.S., the energy saved would be equal to increasing domestic oil production by nearly 50 percent. That is nothing short of revolutionary!

DR. HAROLD SCHOCK, Director
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COMPLEX THERMAL–FLUID PROCESSES
Giles Brereton

Research focusing on thermal fluid processes that are complex by virtue of their transient or turbulent nature. It seeks to improve understanding of both applied problems and the underlying fundamental science.

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CFD NUMERICAL EXPERIMENTS

Farhad Jaberi

Research ranging from high-speed turbulent flows to molecular dynamics of combustion. Using the computational facilities of the MSU High Performance Computing Center (HPCC) for large-scale simulations, our research group carries out fundamental research of practical relevance.

BIOFUELS PRODUCTION & CHARACTERIZATION

Dennis Miller & Carl Lira

Research focused on the development of biofuel formulations using new catalytic reaction pathways from biomass to final products, novel processing approaches such as reactive separations and multiphase reactors, and computational process simulation and molecular modeling. Biofuel characterization incorporates both physical and chemical properties to ensure blending compatibility with existing fuels, proper volatility range, sufficient energy content, and low-temperature viability.

COMBUSTION CHAMBER DIAGNOSTICS

Harold Schock

Research into flow and combustion phenomena in internal combustion engines using laser-based experimental techniques and numeric simulations with a goal of improving efficiency in engines designed to accommodate new fuels and new fuel properties. Research focuses on controlling the fuel-air mixture and turbulence within the combustion chamber, studying various flow control strategies.

REDUCED KINETIC MODELING OF RENEWABLE FUELS

Elisa Toulson

Research associated with chemical kinetics modeling for an improved understanding of the combustion of new renewable fuels. Because biodiesel oxidation chemistry is complicated to model directly, and existing surrogate kinetic models are very large (making them computationally expensive), we have focused on reduced chemical kinetic models of biofuels as a way forward in enabling simulation of renewable fuel combustion.
Research examining problems related to combustion, materials flammability, and fire. Current research foci include structural fire research, plasma-assisted combustion research, counterflow diffusion flame burner research, and material flammability in microgravity conditions (on behalf of NASA). This facility has been employed in materials flammability research for clay-based nanocomposites, xGnP composites consisting of nano-graphite in matrix blends, and for consulting work involving new materials.

**THERMEOLECTRIC CONVERSION IN AN IC-POWERED VEHICLE**
Harold Schock, Guoming Zhu & Giles Brereton

Research in thermoelectric power generation involving recovering waste heat from diesel engines that is then used to extract energy to help power the vehicle. The goal is to improve fuel economy of large trucks by 5 percent in the next few years. Research is translated by MSU’s hybrid vehicles team for application to auto components to maximize the efficiency and affordability of hybrid models. MSU is home to one of the most advanced thermoelectric power generation research groups in the world.

**ELECTRIC POWER CONVERSION**
Binsgen Wang

Research dedicated to gaining fundamental understanding of electric power conversion systems and providing innovative solutions to improve system reliability and efficiency. Electric Power Conversion Lab research activities are mainly in the areas of: (1) development of novel power converter topologies that feature high reliability, efficiency modeling, modulation and control of power electronic systems, and (2) application of power converters as grid interface for renewable energy sources and in high-performance electric drive systems.

**POWER ELECTRONICS & MOTOR DRIVES**
Fang Peng

Research and development of power conversion technology and motor control for renewable energy, utility and transportation applications. Research focuses on enabling technologies to transform today’s transportation and electrical power: from generation to transmission to distribution to utilization into more secure, more sustainable, more intelligent, more reliable, and more efficient energy generation–delivery–utilization systems.
ADVANCED POWERTRAIN & ENGINE CONTROL
Guoming Zhu

Research targeted at applying advanced control theories and technologies to hybrid powertrain optimization and control, and to the control of the internal combustion engine and its subsystems to develop real-time control strategies for the best fuel economy within a given level of emissions. The Automotive Control Lab investigates closed-loop combustion control of internal combustion engines, by applying modern control theories to develop feed-forward and feedback strategies for SI (spark ignited) and HCCI (homogeneously charged compression ignition) combustion controls through optimized spark timing, EGR (exhaust gas recirculation) rate, and engine valve timings and lift and for the combustion mode transition between SI and HCCI operations.

ADVANCED HYBRID VEHICLE EXPERIMENTS
Harold Schock & Guoming Zhu

Research within the Ford Powertrain Laboratory provides testing and measurement of powertrain performance in advanced hybrid vehicles as they are subjected to a broad range of conditions. The lab conducts real-time simulations using a control system configured to simultaneously and independently control each wheel of up to a six-wheeled vehicle. It is ideally suited for the investigation of hybrid applications, including medium- and heavy-duty configurations.

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- Air Force Office of Scientific Research (AFOSR)
- Air Force Office of Scientific Research — National Science Foundation (AFOSR–NASA)
- American Chemical Society Petroleum Research Fund, Argonne National Laboratory (PRF–ANL)
- Arnold and Mabel Beckman Foundation
- Benteler Corporation
- Chrysler Corporation
- Claytech/In-Pore Testing
- Coca-Cola Company
- Delphi Automotive
- Department of Energy (DOE)
- Department of Energy, Defense Advanced Research Projects Agency (DARPA)
- Defense Logistics Agency (DLA)
- Defense University Research Instrumentation Program, Air Force Office of Scientific Research (DURIP)
- Environmental Protection Agency (EPA)
- Ford Motor Company
- General Motors Corporation
- Gongda Power Company
- HCl CleanTech
- National Aeronautics & Space Administration — Jet Propulsion Laboratory (JPL)
- Michigan Economic Development Corporation (MEDC)
- Michigan State University, Composite Vehicle Research Center (MSU-CVRC)
- Michigan State University Foundation
- National Aeronautics & Space Administration (NASA)
- National Corn Growers Association (NCGA)
- National Science Foundation (NSF)
- Office of Naval Research (ONR)
- Science Applications International Corporation (SAIC)
- State of Michigan
- Tecumseh Products
- Tank Automotive Research, Development and Engineering Center (TARDEC), United States Army
MEASUREMENT AND MODELING OF DROPLETS AND FUEL SPRAYS

As the energy demands of the US grow, we continue to seek secure, reliable sources of energy-dense fuels for transportation and power generation. Biofuels are one class of potential contributors to our future energy supply, either as pure fuels or as additives to fuels derived from other sources. These fuels are typically injected or sprayed into the combustion chambers of engines, where their evaporation and mixing has a strong influence on the subsequent combustion process and the formation of pollutants.

In these projects, we conduct experiments on biofuel sprays using high-speed cameras and laser diffraction to determine the sizes of droplets and their break-up characteristics. We also use these measurements to verify the mathematical models we develop for evaporation of individual droplets. We use these theoretical and experimental approaches to describe the behavior of droplets of existing, new, or hypothetical biofuel blends of arbitrary composition. These models can be used to design fuels with prescribed droplet behavior and to model the role of fuel droplets in large-scale simulations of combustion, which we use to predict combustion efficiency and pollutant formation and to optimize combustion chamber design. Current research projects focus on measurement and predictive modeling of droplets in biofuel sprays.

SOOT TRANSPORT, DEPOSITION, AND MITIGATION IN EXHAUST AND EGR SYSTEMS

The transport of soot in gas streams and its deposition on cold surfaces is a common feature of exhaust systems that is poorly understood and rarely incorporated into combustion system design, even when thermoelectric energy recovery is sought.

We are currently developing models and mathematical solutions for the thermophoretic and diffusive transport of soot in duct flows and are exploring ways in which flow unsteadiness can enhance or reduce soot deposition on cold heat-transfer surfaces.
DNS AND LES OF SUPersonic TURBULENT FLOW

Essentially exact computations of turbulent supersonic wall-bounded flows can be carried out by direct numerical simulation at low Reynolds numbers. The computational demands of this approach will make it impractical for calculation of flows during knocking combustion for the foreseeable future and so simplified models, in the form of large-eddy simulations, appear to be the most promising alternative. In this research, we develop sub-grid-scale models of turbulence in compressible shear flows and test them against data from direct numerical simulations. Models which perform well in complicated flows such as the ramp compression flow, for which the predicted shock structure and turbulence levels are shown in the accompanying figure, can be expected to provide accurate predictions of flow and combustion in engine cylinders.

TURBULENT FLOWS IN ENGINES

A major difficulty in understanding turbulent flow in engine cylinders arises from the large degree of variation in the flow from one cycle to the next, possibly because of effects like slight differences in each air inflow past axisymmetric valves.

In this work, which is based on analyses of in-cylinder measurements of planar velocity fields, we have developed a novel technique for identifying the turbulence as the part of the velocity field that loses correlation over an integral scale of a few millimeters, based on stochastic estimation theory. Having identified the turbulent velocity field, we can then isolate the phase-conditioned and cycle-to-cycle variation components of velocity, and use this technique to evaluate the extent to which intake design changes can enhance or reduce the cycle-to-cycle variation, and hence the controllability, of the engine.
Notes Pages
Notes Pages
CONTROL OF COMBUSTION FOR IMPROVED EFFICIENCY & LOWER EMISSIONS

NUMERICAL EXPERIMENTS
GAS TURBINE COMBUSTOR

- Combustor geometry
- New biofuels and energetic fuels
- Fuel injectors, spray parameters, droplet size and velocity distribution, injection frequency
- Fuel-gas mass loading and premixing
- Equivalence ratio
- Inlet gas preheating
- Inflow turbulence and mean flow oscillations
- Operating pressure
- Lean homogeneous or flameless combustion

NUMERICAL EXPERIMENTS
INTERNAL COMBUSTION ENGINE

DOUBLE SWIRL SPRAY BURNER

SPRAY-CONTROLLED DUMP COMBUSTOR

C<sub>7</sub>H<sub>16</sub> & MASS FRACTIONS IN A DUMP COMBUSTOR

MSU THREE-VALVE DISI ENGINE

CA = 220°
Under the same engine operating conditions, biodiesel and standard diesel combustion behave very differently. There is a tremendous opportunity for improving combustion efficiency/emissions if/when we better understand turbulence-spray-combustion interactions.

Our numerical experiments with the new MSU LES/FMDF model indicate that engine performance can be greatly improved by changing the fuel composition or spray parameters.
A strength of the EARL effort is the capability to produce and characterize sufficient quantities of next-generation biofuels to demonstrate performance in extended engine tests. The Biofuels Production & Characterization Laboratories develop new biofuel formulations through research in new catalytic reaction pathways from biomass to final products, novel processing approaches such as reactive separations and multiphase reactors, and computational process simulation and molecular modeling. Pilot-scale equipment facilitates biofuel production in up to one-hundred-gallon quantities. Biofuel characterization incorporates both physical and chemical properties to ensure blending compatibility with existing fuels, proper volatility range, sufficient energy content, and low-temperature viability.

**ROUTES TO BIOFUELS**

**ADVANCED BIOFUEL BLENDS EXPAND THE DIESEL FEEDSTOCK POOL TO CARBOHYDRATES**

**KETONIZATION OF BUTYRIC ACID TO 4-HEPTANONE:**
A CLEAN, EFFICIENT DEOXYGENATION ROUTE

- Butyric acid formed via fermentation of carbohydrate (starch, cellulosic) feedstocks
- MSU Miller lab has demonstrated >98% selectivity to 4-heptanone in continuous process with basic metal oxide catalyst
- CO₂ and water are the only by-products: all combustion energy retained
- Clean, “green” non-polluting process: no by-products and no solvent required
METHODS

BUTYRIC ACID FERMENTATION LEADS TO SEVERAL BIOFUEL SPECIES

BUTYRIC ACID FERMENTATION → CONDENSATION REACTION → 4-HEPTANONE ACETONE

ESTERIFICATION → ETHYL BUTYRATE, BUTYL BUTYRATE, ETHYL ACETATE, BUTYL ACETATE

HYDROGENOLYSIS → BUTANOL, ETHANOL

OZONOLYSIS FOR BIOFUEL COMPONENTS

Butyric acid fermentation leads to several biofuel species.

O3 + CH3(18:1, 9c): 23% + MeOH, catalyst → CH3(18:2, 9c, 12c): 51% + MeOH, catalyst → CH3(18:3, 9c, 12c, 15c): 7% + MeOH, catalyst

Methanol, catalyst

Recovery of mixed acids from fermentation at MSU reactive distillation facility.

WATER FERMENTATE → SUCCINIC ACID → CONCENTRATION ACIDIFICATION PURIFICATION → ETHANOL & WATER

Reactive distillation column for esterification.

ETHANOL & WATER → ETHYL ACETATE / ETHANOL & WATER

Succinate ester

ETHANOL & ETHYL ACETATE RECOVERY
FACILITY

- New facility at MBI includes two pilot-scale columns of heights 5.0m and 10.0m of diameter 0.05m with full instrumentation and computer interfacing
- Columns packed with Sulzer Katapak-S structured packing
- Pilot-scale column simulation and commercial-scale design using AspenPlus process simulation software
RESULTS

BLENDED BIOFUELS IMPROVEMENT FOR COLD–WEATHER PROPERTIES: SELECTED CLOUD POINT MEASUREMENTS

<table>
<thead>
<tr>
<th>COMPOSITION</th>
<th>CLOUD POINT TEMPERATURE (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S. Standard Diesel (USD)</td>
<td>-14.75</td>
</tr>
<tr>
<td>50% USD / 50% Dibutyl succinate</td>
<td>-11.6</td>
</tr>
<tr>
<td>50% USD / 50% 4-Heptanone</td>
<td>-17</td>
</tr>
<tr>
<td>50% USD / 50% Butyl butyrate</td>
<td>-18</td>
</tr>
<tr>
<td>50% USD / 50% Butyl nonanoate</td>
<td>-18.1</td>
</tr>
<tr>
<td>50% USD / 50% Dibutyl ether</td>
<td>-23.7</td>
</tr>
<tr>
<td>Jet fuel</td>
<td>-52.53</td>
</tr>
<tr>
<td>50% Jet fuel / 50% Dibutyl succinate</td>
<td>-49.5</td>
</tr>
<tr>
<td>50% Jet fuel / 50% Butyl butyrate</td>
<td>-56.9</td>
</tr>
</tbody>
</table>

U.S. STANDARD DIESEL IN MIXTURES WITH VARIOUS ADDITIVES

TARGET

JP–8 FUEL SPECIFICATIONS: EXAMPLE TARGET FOR BIOFUELS

<table>
<thead>
<tr>
<th>KEY CHALLENGES FOR BIOFUELS:</th>
<th>MINIMUM</th>
<th>MAXIMUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flash point (°C)</td>
<td>38</td>
<td>68</td>
</tr>
<tr>
<td>Density (g/cc)</td>
<td>0.775</td>
<td>0.84</td>
</tr>
<tr>
<td>Freezing point (°C)</td>
<td>-47</td>
<td></td>
</tr>
<tr>
<td>Heat of combustion (MJ/kg)</td>
<td>42.8</td>
<td></td>
</tr>
<tr>
<td>Sulfur content (wt%)</td>
<td></td>
<td>0.3</td>
</tr>
<tr>
<td>Hydrogen content (wt%)</td>
<td>13.4</td>
<td></td>
</tr>
<tr>
<td>Aromatic content (wt%)</td>
<td>8.0</td>
<td>25.0</td>
</tr>
</tbody>
</table>
CYCLE-BY-CYCLE LAMBDA DURING INJECTION PULSE SWEEP

Cycle-by-cycle lambda values for cycles 27, 33, 38, 42, and 46:
- Cycle 27, $\lambda = 0.77$
- Cycle 33, $\lambda = 0.85$
- Cycle 38, $\lambda = 0.94$
- Cycle 42, $\lambda = 1.00$
- Cycle 44, $\lambda = 1.03$
- Cycle 46, $\lambda = 1.06$

**Directly Injected Spark-Ignition Engine Images @ 17.2 CAD ATDC**

For cycles 27, 33, 38, 42, and 46.
OPTICAL ENGINES: TOOLS FOR STUDYING COMBUSTION IN A REALISTIC ENVIRONMENT

MSU’S TURBOCHARGED OPTICAL DIESEL ENGINE

**CANOLA**

![Images of canola combustion at different ATDC angles](image)

**DIESEL**

![Images of diesel combustion at different ATDC angles](image)
Chemical kinetics modeling is an important aspect of renewable fuel combustion. Alternative fuels such as biodiesel are presently receiving attention as potential substitutes for fossil fuels, as they can be renewable, carbon neutral, and provide energy security. However, biodiesel oxidation chemistry is complicated to model directly and existing surrogate kinetic models are very large, making them computationally expensive. Reduced chemical kinetic models of biofuels are one way forward in enabling simulation of renewable fuel combustion. This type of modeling in conjunction with experimental research allows for an improved understanding of the combustion of new renewable fuels.

**AUTOIGNITION REACTION MECHANISM**

<table>
<thead>
<tr>
<th>STEP</th>
<th>REACTION</th>
<th>RATE COEFFICIENT</th>
<th>REACTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initiation</td>
<td>RH + O₂ → 2R⁺</td>
<td>k₁</td>
<td>1</td>
</tr>
<tr>
<td>Propagation</td>
<td>R⁺ → R⁺ + P + heat</td>
<td>k₂</td>
<td>2</td>
</tr>
<tr>
<td>Propagation</td>
<td>R⁺ → R⁺ + B</td>
<td>f₁k₃</td>
<td>3</td>
</tr>
<tr>
<td>Propagation</td>
<td>R⁺ + Q → R⁺ + B</td>
<td>f₂k₆</td>
<td>4</td>
</tr>
<tr>
<td>Propagation</td>
<td>R⁺ + Q → R⁺ + B</td>
<td>f₃k₇</td>
<td>5</td>
</tr>
<tr>
<td>Branching</td>
<td>B → 2R⁺</td>
<td>k₀</td>
<td>6</td>
</tr>
<tr>
<td>Termination</td>
<td>R⁺ → termination</td>
<td>f₄k₈</td>
<td>7</td>
</tr>
<tr>
<td>Termination</td>
<td>R⁺ → termination</td>
<td>k₅</td>
<td>8</td>
</tr>
</tbody>
</table>

**EXAMPLE BIODIESEL MOLECULES**

- **METHYL LINOLEATE** (C₁₉H₃₄O₂), A METHYL ESTER PRODUCED FROM SOYBEAN OR CANOLA OIL AND METHANOL
- **ETHYL STEARATE** (C₂₀H₄₀O₂), AN ETHYL ESTER PRODUCED FROM SOYBEAN OR CANOLA OIL AND ETHANOL

**RAPID COMPRESSION MACHINE CFD MODEL**

- Multi-level experiment runs 1, 2, & 3
- Fuel = DBE
- Compression ratio = 7.75
- T₀ = 295K, P₀ = 1 ATM

- Overall ignition delay
- End of RCM compression stroke
- First stage ignition delay due to low temperature heat release
- Pressure increase due to RCM compression

**PRESSURE VS TIME**

- Time (ms)
- Pressure (atm)
- 0 5 10 15 20 25 30
- 25 30 35 40
AFTER-TREATMENT SYSTEMS FOR EMISSIONS CLEANUP

The development of increasingly efficient automotive exhaust after-treatment technologies is required to meet mandated emission standards for both gasoline and diesel vehicles. One method of improving exhaust after-treatment technologies is through improvements to exhaust flow uniformity. Non-uniform exhaust flow distribution across automotive catalytic converters affects warm-up, light-off time, aging, and conversion efficiency. A second benefit of the improved flow uniformity is reduced after-treatment expense due to the reduced requirement for expensive precious metal catalysts. The development of after-treatment technologies can be further enhanced through CFD simulations using chemical kinetics to model the surface chemistry that occurs between the exhaust gases and the different catalysts and particulate filters in the after-treatment systems.

KINETIC MODELING OF AFTER-TREATMENT SYSTEMS

Diesel selective catalytic reduction (SCR) catalyst with urea injection (IFP–Powertrain Engineering)
STRUCTURAL FIRE RESEARCH
This diagram above shows a pictorial representation of a structural fire in a compartment. The drawing represents research conducted in the MSU Combustion Laboratory on structural fires involving weakening of structural members and eventual collapse of the structure. Civil Engineering houses the MSU Fire Furnace, which is capable of testing large structural members in simulated fire conditions.

NATIONAL AERONAUTICS & SPACE ADMINISTRATION (NASA) RESEARCH
Flame spread pattern for Narrow Channel Apparatus (NCA). Flame spreads from left to right as the incoming air flow is from the right. This is known as opposed flow flame spread. The material is research-grade cellulose. The flame and flamelet patterns are visible.
COUNTERFLOW DIFFUSION FLAME BURNER RESEARCH
The MSU Counterflow Diffusion Flame Burner (CFB) is currently under development and construction. Spray fuel flows from the bottom nozzle vertically toward the oxidizer flow that is directed downward. The two streams (fuel and oxidizer) never mix. Instead, they meet at the Diffusion Flame. The upward curvature at the ends of the flame is caused by buoyancy. The MSU Counterflow Diffusion Flame Burner will be used to study pulsating fuel injection — a highly unsteady process.

PLASMA-ASSISTED COMBUSTION RESEARCH
Premixed flames with added plasma power. Note the difference in flame size and intensity with only one additional watt of plasma power to the flame.
OBJECTIVES
- Show how advanced thermoelectric generators (TEGs) can provide a cost-effective solution for improving fuel economy and idle reduction for an OTR truck
- Demonstrate steps necessary to develop kW-level TEGs
- Develop TEG fabrication protocol for module and system demonstration using non-heritage, high-efficiency thermoelectric (TE) materials
- Determine heat exchanger and insulation requirements needed for building efficient TEGs
- Design and demonstrate power electronics for voltage boost and module fault bypass in a TEG
- Specify unresolved issues which impede TEG implementation

ACCOMPLISHMENTS
- System for lab-scale production of modules completed
- Un-insulated single couple temperature cycling test successful
- Integrated Couple Bypass Technology has been proposed and demonstrated permitting high levels of series configurations for couples and modules in TEGs
- A Generation 3 100–200 W generator has been constructed and operated, ~1W-in⁻³ possible including power electronics
- A graded layer system for hot side interfaces has been developed and demonstrated
- Highly insulated modules have been demonstrated; greater thermal stresses exhibited
ANNEALING. This mixture is annealed, converting the skutterudite precursors into a homogeneous compound.

DOUBLE GLOVE BOX. All powder processing and die loading for the thermoelectric materials is performed in an inert atmosphere inside the double glove box, which contains a motorized mortar and pestle, a sieve shaker, a planetary ball mill, a hydraulic cold press, and an electronic balance.

HOT-PRESSED BILLETS.

COUPLES. N- and P-type leg pairs are bonded together with a finned heat exchanger to form thermoelectric couples.

5W MODULE. 10-couple modules are assembled to house CBT components, improve unit durability, and establish common a cold side heat exchanger.

FULLY ASSEMBLED TEG. A cylindrical air diffuser directs the heat flow onto the couples via jet impingement.

GEN 3-TEG UNDER TEST.

MSU–DESIGNED 100KVA PERMANENT MAGNET AC GENERATOR

-normal operation-

DIAGNOSED BEARING FAULT
SHORT CIRCUIT
OPEN CIRCUIT
PARTIAL DEMAGNETIZATION
SENSOR FAILURE
FULL DEMAGNETIZATION

PREVENTIVE MAINTENANCE

MSU–DESIGNED 100KVA PERMANENT MAGNET AC GENERATOR OFFERING A COMBINATION OF HIGH EFFICIENCY AND HIGH POWER DENSITY.

OPTIONS FOR CONTINUED OPERATION OF THE ELECTRIC POWERTRAIN IN THE EVENT OF A FAILURE ARE SHOWN BELOW IN A DECISION TREE TO OPTIMIZE DRIVING RELIABILITY.
FINITE ELEMENT ANALYSIS OF THE FIELD—FERRITE AND SMCO MOTORS

Using finite element models coupled with experiments, MSU engineers design and build electric motors, some with ferrite and samarium cobalt armatures.

MSU STUDENT-DESIGNED AND -CONSTRUCTED HYBRID ELECTRIC VEHICLE

MSU student engineers often choose to participate in application projects along with their coursework. Shown is a student designed and constructed vehicle named "Spartan Charge."
EFFICIENCY OPTIMIZATION OF ELECTRIC DRIVE SYSTEM
Overall system efficiency optimized through minimization of power converter loss and augmentation.

SIMULATED RESULTS SHOWING FAULT-TOLERANT POWER CONVERSION TOPOLOGY
FOR SERIES HYBRID ELECTRIC VEHICLES
- Improves reliability with minimal increased part count
- Provides continuous full-power post-fault operation
PROPOSED THREE-PHASE MOTOR DRIVE SYSTEM SHOWING A REDUNDANT LEG

SIMULATED RESULTS FOR THREE-PHASE DRIVE SYSTEM WITH REDUNDANT LEG

Results showing performance when a fault is introduced.
The Power Electronics and Motor Drives Lab consists of a low-voltage (three-phase 480 V) lab and a medium-voltage (three-phase 6,000 V) lab for conducting research, development, and testing of power converters/inverters and motor drives from a fraction of kVA to ten MVA. Working collaboratively with government laboratories, industry, and other universities, projects have ranged from small power converters with power less than 1 kW to multilevel inverters up to megawatts, and motor drives.

**RESEARCH SCOPE & AREAS**

- Advanced power conditioning systems for renewable energy sources such as photovoltaic and wind power from one kW to multi-MW systems and grid-connection controls and protections.
- High power density, high temperature, and low cost power converters and inverters for hybrid electric vehicles (HEV), plug-in HEVs, and pure electric vehicles (EVs).
- High-voltage high-power converters for power system applications such as FACTS devices including static synchronous compensator (STACOM), unified power flow controller (UPFC), etc.
- MW converters and inverters for large motor drives, battery energy storage, and mass transit systems.
- Advanced power electronics circuit topologies and controls: from intelligent gate drives for MOSFETs and IGBTs to new converter/inverter circuitries, from battery protection/voltage balancing circuits to circuit intelligence for self-healing, diagnosis, and prognosis.
RESEARCH HIGHLIGHTS & ACHIEVEMENTS

- A new power conversion technology—Z-source topology—has been developed to achieve buck and boost operation and to overcome the drawbacks of the traditional technology. The new technology is very suited for power conditioning of renewable energy sources such as solar and wind power.
- New multilevel converter/inverter topologies have been developed and demonstrated to achieve high voltage, high power, high efficiency, and high power density.
- High power converters/inverters have been developed for various applications from large motor drives to power system applications. Many of them have been commercialized.
- Funding from more than 30 companies, institutes, and government agencies.
CRANK–BASED REAL–TIME ENGINE MODEL
For closed-loop combustion control, in–cylinder pressure and temperature are critical information for the HIL simulations. This real–time engine model uses the mean–value model for intake and exhaust flow dynamics, crank–based combustion model for MFB (mass–fraction–burned), in–cylinder pressure, and temperature signals; and a combustion event–based model for fuel injection, ignition, and engine torques. This engine model is capable of simulating engine combustion modes such as SI (spark ignited), HCCI (homogenous charge compression ignition), and SI–HCCI (hybrid combustion mode that starts at SI combustion and ends with HCCI combustions). This model has been implemented into the dSPACE real–time simulation environment.

CLOSED LOOP COMBUSTION CONTROL
A prototype engine controller has been developed for closed loop combustion control utilizing the in–cylinder information, such as pressure and/or ionization, for combustion control. The developed controller samples the in–cylinder pressure and ionization signals at every crank degree and calculates engine IMEP (indicated mean effective pressure), MBT (minimal advance for the best torque), MFB (mass fraction burn), and SOC (start of combustion) in real–time. These calculated engine variables are used for combustion feedback: (1) engine MBT timing control, (2) retard limit (combustion stability control), (3) EGR control with guaranteed combustion stability, (4) combustion stability, and (5) combustion mode transition.
Opal-RT based engine prototype controller

Harness breakout box

dSPACE-based real-time simulator
SI AND HCCI COMBUSTION MODE TRANSITION CONTROL

The SI and HCCI mode transition control utilizes two-step valve lift and electrical cam phasing systems. With the help of the hybrid (SI–HCCI) combustion mode during mode transition, the LQ optimal throttle and iterative fueling controls provide smooth combustion mode transition between SI and HCCI combustion.

OTHER CONTROL–RELATED RESEARCH

ROBUST GAIN–SCHEDULING CONTROL
- Gain–scheduling control of engine air–to–fuel ratio
- Gain–scheduling control of engine hydraulic and electrical variable valve timing system
- Constrained LPV–based gain–scheduling control

SMART FUEL CONTENT DETECTION
- IMPC (ionic polymer–metal composite)–based fuel content detection sensor
- Detecting flow media properties such as viscosity
**BIO–FUEL LNT (LEAN NOX TRAP) REGENERATION CONTROL**

This research integrates the on-line adaptive biofuel content detection and closed loop AFR (air-to-fuel ratio) tracking control during the LNT regeneration. The stability of the adaptive control system during the steady state and biofuel content transition operations is guaranteed. Gain-scheduling control is used to improve the system performance.
FORD POWERTRAIN LABORATORY

This facility is equipped with six dynamometers with over 1000 kW worth of absorption capability. Room temperature can be maintained from 70–120°F, making it ideally suited for the investigation of hybrid applications, including medium- and heavy-duty configurations. The working area will accommodate a vehicle 3m in width and up to 8m in length. The control system is configured for simultaneous and independent control for each wheel of up to a six-wheeled vehicle, allowing experiments on a drive cycle of interest.
HYBRID POWERTRAIN CONTROL AND OPTIMIZATION

The figure above shows development of the Simulink-based hybrid powertrain and vehicle models for real-time simulations. This real-time powertrain model can be integrated with the TruckSim vehicle model to be used for HIL (hardware-in-the-loop) simulations.

The diagram below shows the HIL simulation environment at MSU that simulates a mediate-duty serial and power split powertrain consisting of two PM electrical machines, an electrical generator, engine, transmission, and battery.
**ENERGY & AUTOMOTIVE RESEARCH LABORATORY**

**DIRECTOR:** Harold Schock, Professor, Mechanical Engineering  
**GRADUATE STUDENTS:** Cody Squibb, Andrew Hulsand, Chao Cheng, Ravi Vedula (PhD students); Charles Maines (M.S. student)

A significant portion of the work conducted in the Engine Research Laboratory uses motored and firing optical engines. During the past quarter century, MSU has designed and constructed more than 20 optical engine assemblies, from rotary, spark-ignition to diesel configurations. A hallmark of this work has been our ability to use advanced laser diagnostics to characterize combustion and flow in realistic assemblies.

The Thermoelectric Applications Center is also located in this laboratory. This is one of the few places in the world where one can conduct all of the steps needed to build a demonstration thermoelectric generator in a range of 100 to 1,000 watts. Uniquely, this allows the evaluation of new materials as they are developed in devices that have commercially viable applications.

**ADVANCED POWERTRAIN & ENGINE CONTROL GROUP**

**LEADER:** Gouming (George) Zhu, Associate Professor, Mechanical Engineering  
**GRADUATE STUDENTS:** Andrew White, Xuefei Chen, Shupeng Zhang, Jie Yang (PhD students); Ping Mi (M.S. student)

The Control Room facility will be primarily set up for cold start testing, as well as operation under conditions as low as −40°F.

The Automotive Control Lab investigates closed-loop combustion control of internal combustion engines, by applying modern control theories to develop feed-forward and feedback strategies for SI (spark ignited) and HCCI (homogeneously charged compression ignition) combustion controls through optimized spark timing, EGR (exhaust gas recirculation) rate, and engine valve timings and lift and for the combustion mode transition between SI and HCCI operations. We also study the optimization and control of the hybrid powertrain, which consists of many subsystems, such as internal combustion engines, electrical machines, transmission, and so on. Our goal is to develop real-time control strategies for the best fuel economy within a given level of emissions. Real-time prototype controllers (Opal-RT, dSPACE, and Mototron) and HIL (hardware-in-the-loop) simulators (Opal-RT and dSPACE) are used for control strategy development and validations. Control-oriented real-time hybrid powertrain models and engine models of SI, HCCI, and SI–HCCI hybrid combustions are developed and used for HIL simulations and model-based powertrain controls.

**BIOFUEL SPRAYS GROUP**

**LEADER:** Giles Brereton, Associate Professor, Mechanical Engineering  
**GRADUATE STUDENTS:** Sriram Raghunath, Meisam Mehravaran, Farid Roshanghalb (PhD students)

The Fuel Spray Laboratory is dedicated to experimental measurements of liquid sprays and their physical properties. The laboratory has several systems that deliver pre-heated, cooled or ambient-temperature fuels at controlled pressures to injectors and atomizers which can be operated under computer control in either continuous or pulsed modes. Its measurement capabilities include a laser Doppler and a phase Doppler anemometer, a Malvern Spraytec laser-diffraction measurement system, high-speed digital and film cameras, pulsed-laser
illumination systems, and a LaVision Spraymaster laser sheet system for spray pattern analysis.

COMPUTATIONAL FLUID DYNAMICS GROUP
LEADER: Farhad Jaberi, Professor, Mechanical Engineering
GRADUATE STUDENTS: Thomas Almeida, Husam Abdulrahman, Shalabh Srivastava, Shiwei Qui, Abolfazl Irannejad, Avinash Jammalamadaka, Saleh Rezaieiravesh (PhD students); Araz Banaeizadeh, Zhaorui Li (postdocs)

The Computational Fluid Dynamics (CFD) Laboratory (www.egr.msu.edu/cfd-lab) at MSU includes 4 faculty and about 25 graduate students who are working on a variety of thermal/fluid problems ranging from micro to very large scales. The past and current projects in the lab include several joint multi-PI projects as well as many small single-PI ones. Professor Jaberi is coordinating and managing all the research efforts and educational activities at the lab. He is also responsible for the upgrading of the facility and equipment. For small- and mid-size simulations, flow visualization, software/algorithms/model development, and post-processing of data there are a 16-processor parallel PC cluster machine and many SUN/SGI servers and PCs available in the lab. These machines are equipped with state-of-the-art visualization, parallelization, and computational software (MPI, PVM, Tecplot, MathLab, etc.) and are linked through a high-speed network. For large-scale simulations, we are using the supercomputers in the High Performance Computer Center at MSU. The center hosts a symmetric multi-processor (SGI-SMP) machine, distributed memory clusters, and long-term mirrored storage systems.

The Combustion Laboratory primarily examines problems relating to combustion and fire research. The Laboratory houses the newest FTT Cone Calorimeter (CC) in an American university. As of February 2012, it is one of the newest in the U.S. The CC is used to measure the flammability of combustible materials. This facility has been employed in materials flammability research for clay-based nanocomposites, xGnP composites consisting of nano-graphe in matrix blends, and for consulting work involving new materials. All cone tests are ASTM E1354, NFPA 271, and ISO 5660 approved; thus our research qualifies as flammability tests. In CC tests a flat surface undergoes material degradation by flame. The heat flux and surface regression are one-dimensional. Global burn progress is monitored with mass loss, CO2, O2, heat release, and ignition time. Research is also conducted on the MSU Narrow Channel Apparatus (NCA), a ground-based facility designed to simulate material flammability in microgravity conditions. This research is being carried out for NASA and, if the project funding continues, this experiment will be flown in space around 2018. Other research projects involve the examination of combustion in Wave Disc engines. A premixed flame combustion facility has been constructed and is used to make very-high-speed measurements of flame propagation in rectangular cylinders. This research is funded by ARPA-DOE. Other projects of interest include the construction of a Counterflow Diffusion Flame Apparatus for measuring pulsatile diffusion flame combustion, the construction of a Limited Oxygen Index combustion...
calorimeter (LOI calorimeter), and a facility for measuring the conductivities of soils used for Green Roofs. The latter is a project Wichman has become involved with (the MSU Green Roof Group).

**RENEWABLE FUELS & IGNITION ENHANCEMENT GROUP**

**LEADER:** Elisa Toulson, Mechanical Engineering  
**GRADUATE STUDENTS:** Gerald Gentz, Andrew Koch (PhD students)

The primary function of the Renewable Fuels and Ignition Enhancement Laboratory is to study the chemical kinetics of renewable fuel combustion and ignition enhancement technologies. Currently, efforts are being made to develop a reduced kinetic model for biodiesel fuels and fuel blends that can be used in CFD applications. In addition, ignition enhancement technologies for spark ignition engines are being studied to enable low temperature combustion that can reduce both fuel consumption and oxides of nitrogen emissions.

**BIOFUELS PRODUCTION & CHARACTERIZATION GROUP**

**LEADER:** Dennis Miller, Professor, Chemical Engineering & Materials Science  
**GRADUATE STUDENTS:** Arati Santhanakrishnan, Venkata Sai Pappu, Aaron Oberg, Tyler Jordison, Anne Lown (PhD students)

A strength of the EARL effort is the capability to produce and characterize sufficient quantities of next-generation biofuels to demonstrate performance in extended engine tests. The Biofuels Production and Characterization Laboratories develop new biofuel formulations through research in new catalytic reaction pathways from biomass to final products, novel processing approaches such as reactive separations and multiphase reactors, and computational process simulation and molecular modeling. Pilot-scale equipment facilitates biofuel production in up to 100-gallon quantities. Biofuel characterization incorporates both physical and chemical properties to ensure blending compatibility with existing fuels, proper volatility range, sufficient energy content, and low-temperature viability.

**ELECTRICAL MACHINES & DRIVES GROUP**

**LEADER:** Elias Strangas, Professor, Electrical & Computing Engineering  
**GRADUATE STUDENTS:** Shanelle Foster (M.Sc., Project Engineer); Shahid Nazrullah (PhD Postdoctoral Researcher); Jorge Gabriel Cintron-Rivera, Andrew Stephen Babel, Reemon Zaki Saleem Haddad (PhD students); Eduardo E. Montalvo-Ortiz, Arslan Qaiser, Muhammad J Zaheer, Rodney Singleton (M.Sc. students)

The Electrical Machines and Drives Laboratory conducts research and provides education and service in the field of electrical machines and drives. Significant effort has been spent in the last ten years on the design of reliable drives that can withstand a fault and continue operating, as well as methods to detect a fault, predict remaining useful life, and enhance reliability. The laboratory has extensive equipment for development, controlling, and testing of designs of electrical drives, including design software, dynamometers, inverters, sensors, etc. Its graduates have achieved positions of leadership in industry and academia.

**BROWN FOUNDATION ENERGY LABORATORY**

**MORELLI GROUP**

**SEMICONDUCTORS MATERIALS LABORATORY**  
**DOE, ENERGY FRONTIER RESEARCH CENTER**  
**LEADER:** Donald Morelli, Professor, Chemical Engineering & Materials Science

**NICHOLAS GROUP**

**SOLID STATE IONIC MATERIALS LABORATORY**  
**LEADER:** Jason Nicholas, Assistant Professor, Chemical Engineering & Materials Science

The Brown Foundation Energy Laboratory is a shared facility under development with a group from MSU Chemical Engineering. Their primary function is to develop new, high-efficiency thermoelectric materials. MSU was recently named an Energy Fundamental Research Center on thermoelectrics by the U.S. Department of Energy. Much of MSU’s basic work on thermoelectrics will be conducted at this site.
ELECTRIC POWER CONVERSION GROUP

LEADER: Bingsen Wang, Associate Professor, Electrical & Computing Engineering

GRADUATE STUDENTS: Emad Sherif, Yantao Song (PhD students)

The Electric Power Conversion Laboratory is dedicated to gaining fundamental understanding of electric power conversion systems and providing innovative solutions to improve system reliability and efficiency. The research activities are mainly in the following areas:

- Development of novel power converter topologies that feature high reliability, efficiency
- Modeling, modulation, and control of power electronic systems
- Application of the power converters as grid interface for renewable energy sources
- Application of the power converters in high performance electric drive systems

The EPCL is equipped with modern experimentation and instrumentation measures. Currently, the following major equipment has been dedicated for research:

- High-bandwidth digital oscilloscopes, programmable AC and DC electronic load, programmable DC power source, digital signal processor platforms, and high-end personal computers and various simulation software packages.

SHARED FACILITIES

Engine Dynamometers
This facility is equipped with two AC dynamometers capable of absorbing 110 kW and 400 kW respectively.

Cold Room
A walk-in thermal chamber installed in Room E131 ERC-South will be used for hot- and cold-start engine tests, evaluating the performance of biofuels at low operating temperatures and other experiments that require a cold or hot environment. The temperature range is −45 °C (−50 °F) to +65 °C (+150 °F). The chamber is 12' wide × 12' deep × 10' high. Prior to installing the chamber, a 5’ wide × 10’ long steel bedplate was placed in the foundation to provide a secure anchor for the dynamometer and engine cart receiver. During testing, the chamber has a cold flow delivery system that enables us to provide a minimum of 500 scfm of air at −40°C. This delivery system will prevent humidity and condensation buildup during the test.

Ford Powertrain Laboratory
This facility is equipped with six dynamometers with over 1,000 kW worth of absorption capability. Room temperature can be maintained from 70–120°F, making it ideally suited for the investigation of hybrid applications, including medium- and heavy-duty configurations. The working area will accommodate a vehicle 3 meters in width and up to 8 meters in length. The control system is configured for simultaneous and independent control of each wheel of up to a six-wheeled vehicle, allowing experiments on a drive cycle of interest.
Recent Articles & Publications


“Flame Spread over Thin Fuels in Actual and Simulated


“Novel Process for Recovery of Fermentation–Derived Succinic Acid,”


Recent & Current Contracts & Grants

Advanced Propulsion Technologies: “Bidirectional DC–DC Converter for a Starter Alternator”
Air Force Research Lab, Michigan/AFRL: Collaborative Center in Aeronautical Sciences
Air Force Office of Scientific Research, NASA: Hypersonic Propulsion Center
Benteler Corporation: “EGR Cooler Baseline Thermal Testing”
Chrysler, LLC., sub-award with Department of Energy: “Advancing Transportation Through Vehicle Electrification—PHEV”
Claytech: “In–Pore Testing”
Coca-Cola Company: “Green Synthesis of BTX as Intermediates for PET Production”
Delphi Automotive: “Fault Prediction for Permanent Magnet Motors”
Department of Energy: “Design, Construction, and Demonstration of Skutterudite–Based Thermoelectric Generators”
Department of Energy: “Flex Fuel–Optimized SI and HCCI Engines”
Department of Energy: “Novel Biofuel Formulations for Enhanced Vehicle Performance”
Department of Energy: “Powertrain Design and Testing for Hybrid Buses”
Defense Logistics Agency: “Advanced Biofuels for Aviation and Ground Applications”
Environmental Protection Agency: “Development for Future Advanced Vehicle Technologies That Will Improve Fuel Efficiency and Reduce Emissions”
Exxon Mobil Corporation: “High–Voltage Direct–Current Power Transmission for Oil and Gas Applications.”
Ford Motor Company: “Use of Wavelets for the Prognosis of Faults in Electrical Machines”
General Motors: “Combustion and Aftertreatment Regeneration Control for Biodiesel Engines Using Knock and Pressure Sensors”
General Motors Corporation, Research Labs: “Diagnosis of Magnetic Structures and Components for Electrical Machines”
General Motors Corporation: “Fault Diagnosis and Prognosis for the Automotive Starting System”
HCl Clean T echology: “Test Runs on Distillation Column”
Michigan Life Sciences Corridor Fund: “Oxygenation by Liquid Infusion in Medicine/Environment”
Michigan State University, Composite Vehicle Research Center:
“Material Degradation and Flammability of XGnP Composites”
Michigan State University: “Synthesis of Propylene Oxide from
Propylene Glycol”
Michigan State University Foundation, Strategic Partnership Grant:
“Transportation Fuels from Biomass—A Novel, Integrated
Approach to Fast Pyrolysis and Upgrading of Bio-Oil”
National Aeronautics & Space Administration: “A High-Fidelity Model for
Numerical Simulations of Complex Combustion and Propulsion Systems”
National Aeronautics & Space Administration: “Developing the Narrow
Channel Apparatus as a NASA Standard Material Flammability Test”
National Aeronautics & Space Administration, Jet Propulsion Lab: “Leg
Fabrication Using Skutterudite Based Thermoelectric Materials”
National Corn Growers Association: “Advanced Biofuels and Chemicals
from Mixed Alcohols”
National Science Foundation, GOALI/Collaborative Research: “A
Control-Oriented Charge Mixing and Hybrid Combustion Model
for SI-HCCI dual Mode Engines”
National Science Foundation, GOALI: “Reliability Enhancement of
Electric Drive Systems through Failure Prognosis and Fault Mitigation”
National Science Foundation: “Mathematical and Computational Study of
Turbulent Mixing and Reaction”
National Science Foundation: “Toward More Reliable and Efficient Power
Conversion Systems through Intelligent Interactions” (pending)
Office of Naval Research, Northwestern University: “Nanostructured
Chalcogenide-Based Thermoelectric Materials for High-
Efficiency Energy Conversion: Design and Application”
Office of Naval Research, Young Investigator Program: “Ignition and
Oxidation of Bio-Derived Future Navy Fuels”
Science Applications International Corporation: “Advanced Hybrid
Electric Powertrain Program”
Tecumseh Products: “Design of a PMAC Generator”
Tecumseh Products: “Iron Loss Estimation from Finite Element Analysis”
United States Army, Tank Automotive Research, Development and
Engineering Center (TARDEC): “Powertrain Design Aspects and
Evaluation for Heavy-Duty Hybrid Vehicles”