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Using Computational Modeling in the Development and Design of Alternative Powertrain Vehicles

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INTRODUCTION

TODAY'S MOTOR VEHICLES USING CONVENTIONAL FUEL CONTRIBUTE SUBSTANTIALLY TO AIR POLLUTION AND climate change. As such, we can expect that emission standards will continue to get progressively tighter in order to protect human health and the environment. Additionally, the number of vehicles produced annually has been growing steadily over the past few decades and the worldwide fleet will only increase in years to come. Given the current transportation sector's heavy dependence on petroleum fuel, the worldwide demand for oil to propel all of these vehicles is expected to surge. In the U.S., 97 percent of the total fuel consumed by the transportation sector is petroleum-based, more than half of which is imported. With two out of every three people now concerned about climate change and governments concerned with the economic and political implications of volatile oil prices, new alternative powertrain technologies are needed to deliver zero, or near zero, emissions and improved fuel economy. Simulation software designed to optimize product development processes can play a valuable role in identifying cleaner, more fuel-efficient powertrain alternatives. This paper discusses the scope and impact of the problem and explains how computer-aided engineering (CAE) tools such as computational fluid dynamics (CFD) for fluid flow analysis and Finite Element Analysis (FEA) for structural analysis and optimization techniques can be used to design and analyze alternative powertrain technologies and contribute to the achievement of stricter emission standards.

SITUATION OVERVIEW

The ongoing growth in the world's population and industrialization of countries are expected to drive increases in the worldwide automotive fleet. However, the resulting rise in the number of vehicles on the road and the miles traveled come with undesirable consequences: ever-increasing demand for fossil fuel and greater emission of air pollutants with the potential to seriously threaten air quality, global climate and human health.

According to the U.S. Department of Energy, two of the main energy challenges facing the nation in the 21st century are reducing dependence on petroleum imports and reducing pollution and greenhouse gas emissions[1].

Atmospheric concentration of carbon dioxide (CO_2), a greenhouse gas that affects global climate, has increased by more than 30 percent since pre-industrial times, mostly due to the burning of fossil fuels. In urban areas, motor vehicles represent one of the prime sources of air pollution that contains greenhouse gases, and in the U.S. vehicles account for a third of the country's air pollution.

Medical research has linked air pollution to a host of public health concerns including asthma, cancer, heart disease, and birth defects, among others. In 2007, over 158 million Americans lived in areas that did not meet national ambient air quality standards.[2] In parallel, greenhouse gases disrupt the environment and the climate system, leading to a decrease in production of staple foods and an increase in air- and water-borne illnesses. Furthermore, an occurance of abrupt climate change may have implications on national security, as indicated in a report commissioned by the U.S. government.[3]

The International Energy Agency (IEA) estimates that at the current rates the transportation sector's carbon emissions will rise by 75 percent between 1997 and 2020. Calls for action to stabilize atmospheric concentrations of greenhouse gases will require a substantial reduction in, if not elimination of, vehicle emissions.

ZERO EMISSION VEHICLE PROGRAM

In the U.S., the air quality standards are managed by the Environmental Protection Agency (EPA).

California is the only state allowed to set air quality standards more restrictive than the federal law, while the other states are allowed to adopt the California standards. To put cleaner cars on the road, the state established the Zero Emission Vehicle (ZEV) program, which calls for reduction of greenhouse gas emissions by 30 percent in new vehicles by 2016. Under the ZEV program, manufacturers can meet the state's mandate through a base compliance path that allows selling a mix of zero emission vehicles (electric and fuel cell vehicles), advanced technology vehicles (hybrid electric, plug-in and compressed natural gas vehicles) and SULEVs (Super Ultra Low Emission Vehicles that are conventionally powered), or they can instead opt for an alternative path of selling a certain number of fuel cell vehicles.

Currently, 13 other U.S. states have adopted the California's ZEV regulations and five others are in the process of adopting them, which is adding to the need for increased research and development among vehicle manufacturers and spurring advancements in alternative vehicle powertrain technology.

INTERESTING FACT

In very smoggy urban areas, Partial Zero Emissions Vehicle (PZEV) tailpipe emissions are cleaner than the outside air.[6]

QUICK FACTS: USA

- The U.S., with less than 5 percent of the world's population, consumes approximately one-quarter of the world's petroleum[4]
- Nearly half (43 percent) of the U.S. carbon emissions are from oil use[4]
- About 141 million tons of pollution are emitted into the atmosphere each year in the U.S.[5]

QUICK FACTS: CALIFORNIA[6]

- California population (2003): 36 million
- Miles driven every day in California: 825 million
- Miles driven daily by the average California driver: 36
- Pounds of pollutants created daily in California: 5.4 million

INDUSTRY LANDSCAPE

The worldwide vehicle fleet is projected to almost triple by mid-century, reaching 2 billion. To keep global vehicle emissions at today's levels, the average fuel economy of cars and trucks would need to rise to about 60 mpg[7]. To put this target in perspective: the average light vehicle in 2006 got 21.0 mpg, according to the EPA.

While the long-term goal is to develop energy-efficient vehicles that do not require petroleum fuels, the interim focus is on reducing petroleum consumption by making vehicles more fuel efficient. To this end, auto manufacturers have been looking for potential substitutes for the conventional gasoline powered internal combustion engine (ICE) and investing in the development of alternative technologies such as flex-fuel vehicles (FFVs), “clean” diesel vehicles, hybrid-electric vehicles (HEVs), electric vehicles (EVs) and fuel cell powered vehicles (FCVs).

The three main barriers to widespread use of alternative powertrain vehicles are cost, performance and fuel delivery infrastructure. It is reasonable to expect that in the near term the automobile industry will carry on with the strategy of pursuing a combination of powertrain concepts, starting with the most cost-efficient technologies of today and transitioning toward more elaborate technologies over time.

HOW SIMULATION CAN HELP

Regardless of what type of underlying powertrain system is used, buyers ultimately expect vehicles that deliver on fuel economy and meet emission targets without sacrificing performance, comfort and price. Such market requirements put substantial pressure on automobile manufacturers to accelerate the development and testing of multiple technical alternatives in a cost-efficient way. CAE software has been widely embraced by the automobile industry for its ability to help bring new and better products to the market faster and cheaper. As a virtual simulation tool, CAE helps reduce the myriad of design possibilities to the most promising performers without the expense and additional time of having to physically build and test multiple prototypes. Significant improvements of product performance and reliability can be achieved through the implementation of CAE techniques such as parametric CAD modeling, FEA, CFD and multiphysics computer simulations. Further, quality issues can be addressed early on in the design cycle through the use of advanced CAE techniques such as optimization, probabilistic design and topology optimization, which can account for the effects of operating conditions, manufacturing processes and naturally occurring variations in material properties on design performance. CAE is helping the automotive industry bring to market innovative and robust designs with built-in quality.

Following examples illustrate how CAE modeling techniques are being successfully used in the development and design of devices associated with alternative power-train systems.

HEV/EV BATTERY APPLICATIONS

The performance and lifespan of batteries in EVs and HEVs is greatly affected by temperature, prompting an increased focus on the battery thermal control to minimize warranty costs. Hot spots can cause premature failure that degrade overall performance and drive up warranty costs. As battery power capabilities increase, achieving effective thermal control becomes even more important. The

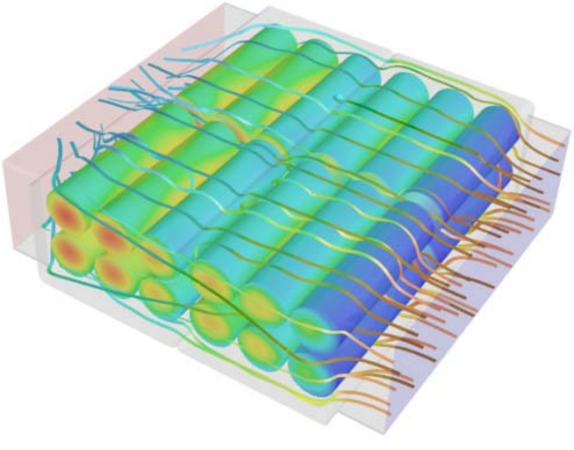
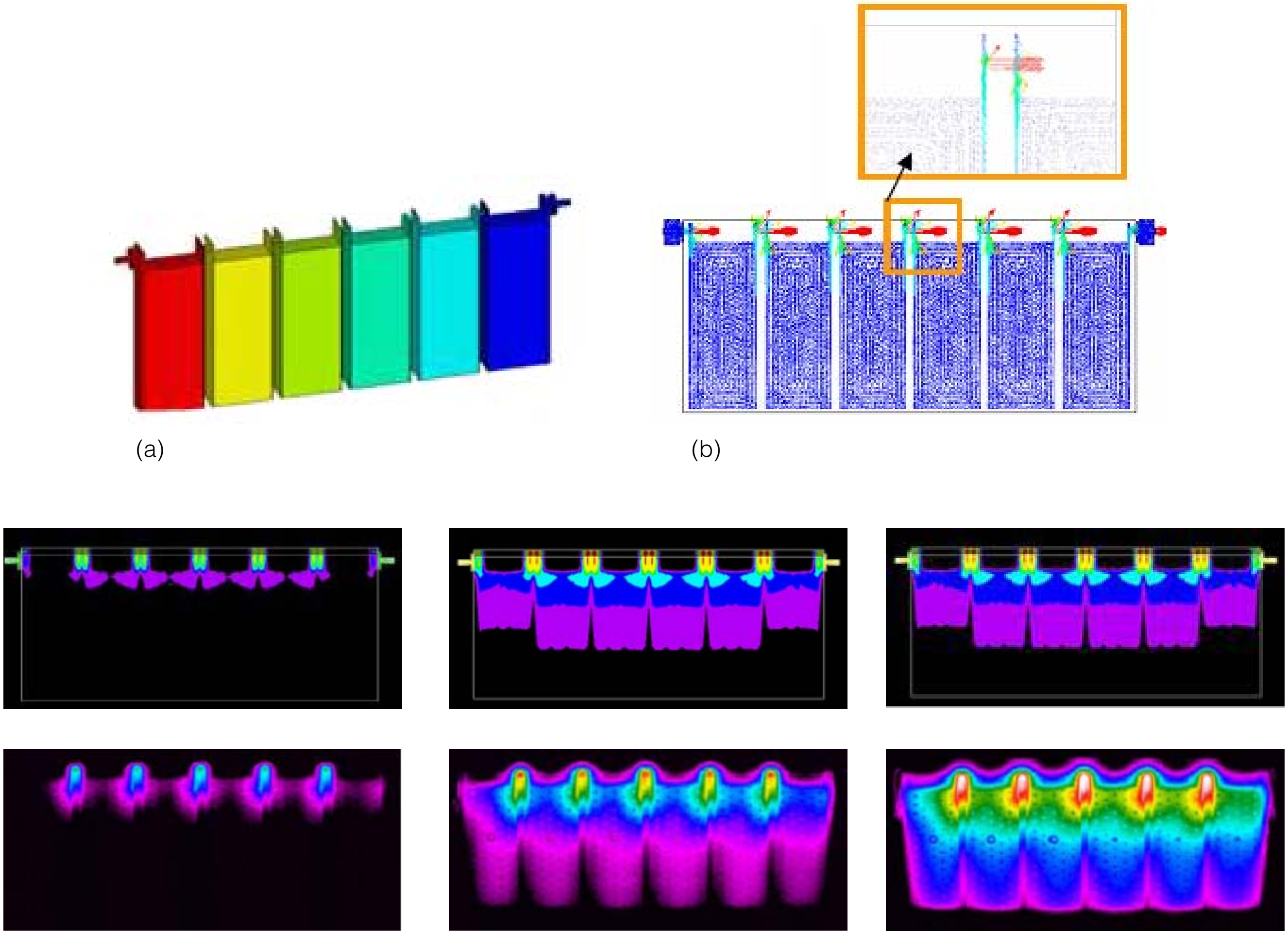


Figure 1: Performance of battery packs depends on performance of individual cells and modules: Cell temperature distribution and flow field in a representative pack.

engineering challenges lay in insuring that battery performance and durability targets are met over a range of ambient conditions — including cold-start and real driving conditions that lead to battery charging and discharging — while shortening development cycle.

Good thermal performance starts with a good design. However, it is challenging to capture and model all the physical elements and details of a cell and drive the design parametrically for simultaneous electrical and thermal modeling while considering performance limits and specifications for optimum efficiency and cost considerations. The process of engineering optimization via highly connected CAE approaches is considered to be the best method.[8] Such an approach involves a multiphysics code that performs both electrical and thermal analysis. Based on the geometry and material properties, electrical resistance of each component is calculated, then heat generation due to the current in the hardware components and heat caused by the electrochemical reactions computed. Temperature distribution in the cell is estimated, allowing for identification of hot spots. Using this approach, the designer can improve the thermal design by reducing resistances, improving the power capability of batteries and avoiding extreme hot spots in cells that lead to premature failures.


(a)

(b)

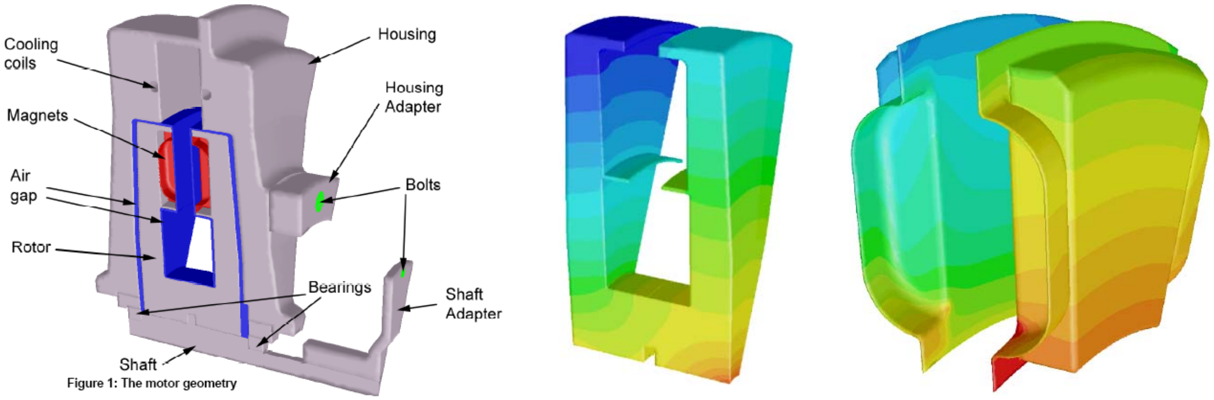
(c)

Figure 2: Battery electrothermal model: (a) Voltage distribution in each cell. (b) Current density in the module with inserting shows the highest current density through the weld junction. (c) Temperature distribution in the case after 2 minutes, 2.5 minutes, and 3 minutes of discharge. Top row simulation results, bottom row thermal images (experiment).[8]
This figure was developed by the National Renewable Energy Laboratory for the U.S. Department of Energy.

HEV ELECTRIC MOTOR

An electric motor is, along with the engine and battery, a key component of any HEV vehicle. It helps propel and accelerate the vehicle and charges the battery via regenerative braking. Electric motors are exposed to elevated temperatures characteristic of a vehicle underhood environment, including thermal effects produced by engine combustion. Reliability of electric motors in such harsh operating conditions depends on effective thermal management that ensures magnets and sensitive electric components are protected from overheating.

CFD analyses of the electric motors that include the effects of air gaps within the motor and the flow of external liquid coolant help in identifying locations of peak temperatures, the heat transfer capability of various components, parts critical to the design of the motor and the effects of rotor speed variation on the motor performance.



(a) (b) (c)

Figure 3: (a) Geometry of an automotive electric motor, temperature distribution on the rotor (b) and permanent magnets (c). Courtesy of Lynx Motion Technology Corp. and Kinetic Artan Technology Corp.

POWER ELECTRONICS

One of the key obstacles to developing next-generation power electronics is achieving efficient cooling within compact environments subjected to high heat fluxes and high temperatures. Exposure of electronic equipment to high temperatures leads to accelerated material failure, reducing the equipment lifetime and reliability.

The number of electronic components in vehicles has been growing steadily over the years and that number is expected to increase in next-generation vehicles. For future power electronics to operate in high-temperature and tight-space environments, innovations in the design of components and systems as well as the development of advanced heat transfer and cooling techniques are required. Two examples related to the management of HEV power electronics thermal issues are presented next.

PROJECTED ANNUAL SALES OF ALTERNATIVE VEHICLES IN 2030[9]

The projected sales of alternative vehicles account for nearly 28 percent of projected new light-duty vehicle sales in 2030, up from just over 8 percent in 2005.

Vehicle Type	Sale Volume	Market Share
Flex-fuel	2 million	10%
Hybrids	2 million	10%
Diesels	1.2 million	6%
Other alternative technology (electric, fuel cell, etc)	0.4 million	2%
	Total:	28%

In the first example, a geometry redesign is required in order to improve the heat transfer capability of a heat exchanger used for inverter cooling. DC-AC conversion in hybrid electric vehicles involves insulated gate bipolar transistors (IGBTs), which require heat exchangers for the removal of large amounts of heat dissipated in the IGBTs. CFD numerical simulations involve diagnosing problem areas in the original heat exchanger design, followed by investigating the effects of modifications to the original geometry shape and orientation. Figure 4 shows the flow field and velocity distribution near the entrance region of a plate style heat exchanger. Suboptimal flow distribution in the original design was making the plate prone to fouling. The revised design yielded more uniform distribution of the flow and enhanced heat transfer, resulting in lower temperatures overall.

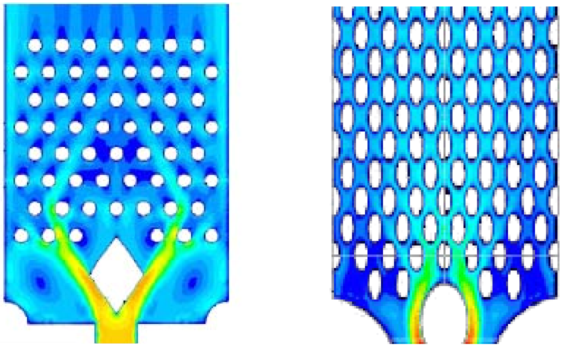


Figure 4: Flow field and velocity distribution for IGBT heat exchanger: (a) at the entrance region of the baseline design, (b) in the revised design.[10]
This figure was developed by the National Renewable Energy Laboratory for the U.S. Department of Energy.

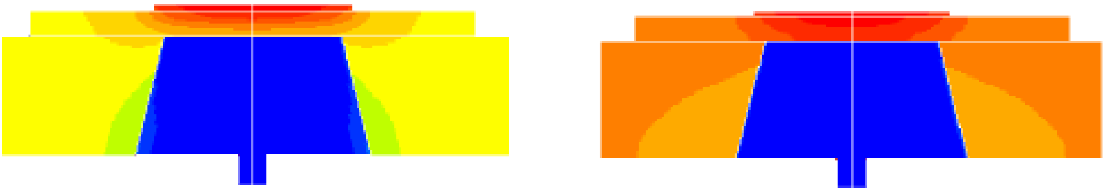


Figure 5: Temperature contours in IGBT package with boiling (left) and without boiling (right). [11]
This figure was developed by the National Renewable Energy Laboratory for the U.S. Department of Energy.

In the second example, the feasibility of enhancing the heat transfer via techniques of impinging jets with phase change for cooling power electronics components is explored. Turbulent jet impingement involving nucleate boiling can provide fairly high heat-transfer coefficients, making it an attractive option for electronics cooling applications. The CFD model was validated against experimental studies on submerged jets involving nucleate boiling and then applied to IGBT package cooling. The results, Figure 5, indicate that boiling yields lower temperatures than single-phase flows, giving evidence of the benefits of boiling jet impingement as a cooling option from a heat transfer standpoint.

FUEL CELL APPLICATIONS

The fuel cell industry has been embracing CAE tools for their ability to guide the engineering design process while reducing development time and cost. Because fuel cells are a relatively new technology, there are still quite a few key technical barriers to overcome before fuel cells can be commercially mainstreamed. Some of the barriers include the need for a full understanding of intricate physics of flow within Polymer Electrolyte Membrane (PEM) fuel cells due to multiphysics and multiscale phenomena, an optimal distribution of hydrogen and oxygen on electrodes, effective flow and thermal management within given packaging limitations, cold-weather operation of the stack, advanced materials and innovative structural designs for onboard storage of hydrogen, resolving safety issues with hydrogen leakage, robust sealing of plate interfaces and more. In addition, reliability issues due to variations in material properties, operating conditions, manufacturing processes and such are of major importance. CAE tools that integrate multiphysics modeling capabilities, optimization techniques, topology optimization and parametric modeling can be of especially good value to fuel cell engineers and designers.

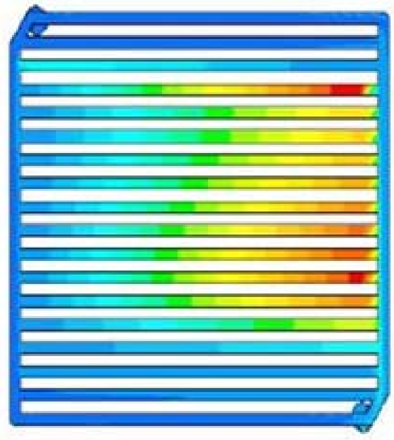


Figure 6: Liquid water concentration on a slice through a cathode channel. Courtesy of Spanish Institute for Aerospace Technolgy.

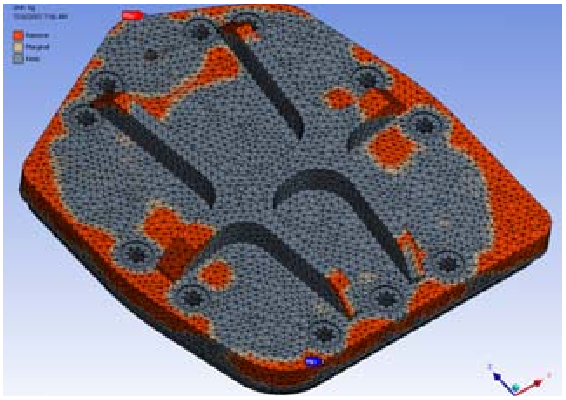


Figure 7: Shape optimization of fuel cell end-plates, showing where material can be removed (red). Courtesy of Advanced Engineering Solutions.

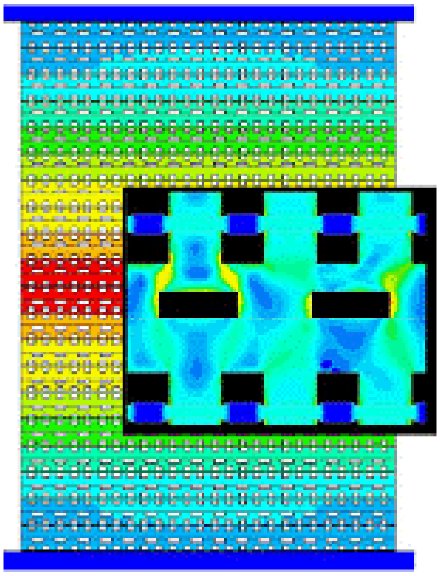


Figure 8: MEA's pressure distribution is impacted by the effect of manufacturing, loading and material variations of a fuel cell stack. [12]

This figure was developed by the National Renewable Energy Laboratory for the U.S. Department of Energy.

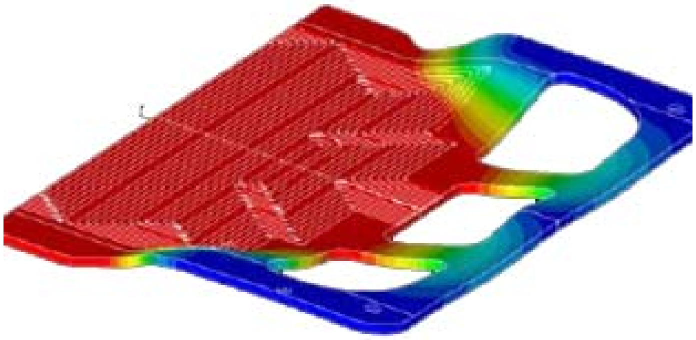


Figure 9: Bipolar plate cracks due to manufacturing process. [12]

This figure was developed by the National Renewable Energy Laboratory for the U.S. Department of Energy.

A sample list of fuel cell related applications where CAE numerical techniques can be used includes: fuel cell stack modeling; design optimization of bipolar and end plates for reduced mass and improved strength; design of alternative gasket and groove configurations of the cooler and cell interfaces for robust sealing; evaluation of the structural integrity and fatigue life of a reformer subsystem subjected to thermal loading, including effects of component placement on flow distribution; and manufacturing process improvement to avoid bipolar plate cracks.

HYDROGEN ICE

A hydrogen burning engine has the potential to outperform both gasoline and diesel engines in terms of efficiency and power density. Today ICE development, including optimization of mixing and combustion processes as well as the development of injection and ignition systems, often involves CFD simulations. To adapt the internal combustion engine for the use of hydrogen requires a good understanding of the physics of mixture formation and combustion processes specific to the hydrogen fuel. The current CFD models for fuel mixing and combustion, however, have been developed for carbon fuels (such as gasoline and diesel) and not validated for hydrogen applications.

Figure 10: High-pressure direct injection hydrogen combustion engine.
Courtesy BMW Group

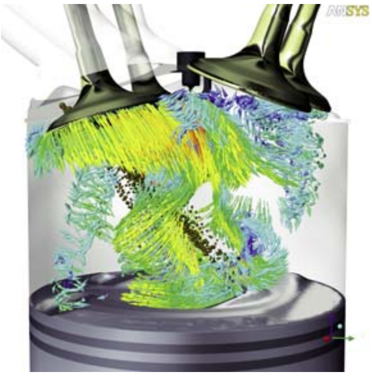


Figure 11: Vortex structures in a GDI engine.
Courtesy BMW Group

A set of hydrogen-specific 3-D numerical models for mixture formation and combustion processes were developed and validated under the Hydrogen Internal Combustion Engine (HyICE) project, a European initiative aimed at the development of a hydrogen-fuelled automobile engine. These numerical models were validated against experimental and open-literature data and implemented within a commercial CFD tool.

CONCLUSIONS

Combustion by-products from conventionally powered motor vehicles are harmful to the environment and human health, and as such have been subject to legislative regulations in the U.S. since the late fifties. As emission standards continue to get progressively stricter, auto manufacturers have been accelerating the development of alternative powertrain technologies. At the moment, multiple alternatives seem to hold promise for the future and further engineering developments will be needed to turn these technologies mainstream. CFD and FEA, proven CAE technologies with broad application across the motor vehicle industry, play an important role in the development of engineering improvements to alternative vehicle powertrains. These improvements are helping to address the needs of the automotive industry to meet tougher air quality standards, as well as to deliver fuel efficient vehicles that consumers are seeking.

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