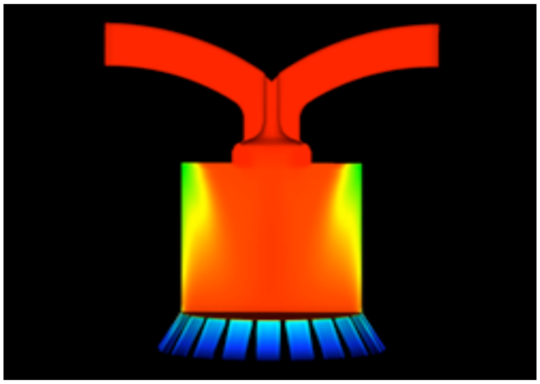
Kettering University researchers visualize environmentally friendly combustion engines

by Jill R. Aitoro

Researchers at Kettering University in Flint, Mich., are using advanced simulation and visualization technologies in search of better exhaust gas recirculation (EGR) systems for cars. University researchers think their work will lead to a two-zone combustion system that is more fuel efficient and environmentally friendly.



Optimizing the air-fuel ratio

For fuel to burn, it needs oxygen. But oxygen is not all that's sucked from the atmosphere into an automobile when a spark-ignition engine is running. Large quantities of nitrogen find their way into the engine as well. When heated, nitrogen reacts with excess oxygen to produce nitrogen oxide (NOx) that flow from exhaust pipes.

For the past 35 years, automobile manufacturers have relied on EGR to control automotive emissions in gasoline engines. The process recently became available in diesel passenger car engines as well.

"EGR is usually used to dilute the inlet charge, which consists of air, by redirecting part of the exhaust into the inlet manifold of the engine," says Bassem Ramadan, associate professor of mechanical engineering at Kettering.

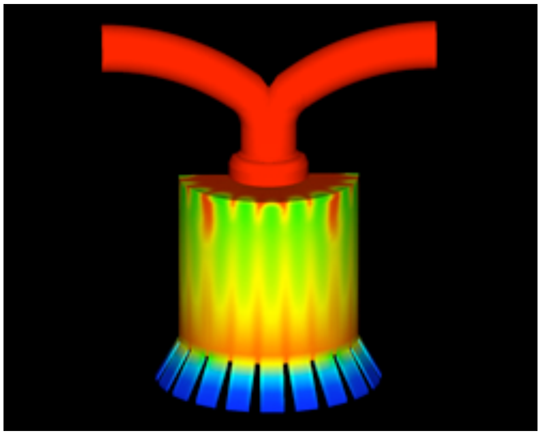
The redirected exhaust gases contain less oxygen because they've already filtered through the engine. The oxygen that does remain is used to burn fuel, with little left over to contribute to contaminants.

EGR dilution has also been suggested as a means to improve low part-load efficiency of engines. Part load, also referred to as part throttle, is when the engine doesn't produce maximum power because the throttle is not fully open. The dilution method introduces large amounts of EGR into the cylinder, reducing the need to throttle the intake system at part load and improving efficiency.

If researchers could further optimize the efficiency of the air-fuel ratio in an EGR engine, more than the environment would reap rewards. Consumers would benefit from fuel economy savings similar to that achieved with diesel engines - up to 30 percent over normal car engines.

Simulating engine processes

In collaboration with the Environmental Protection Agency, which is also funding the project, Ramadan and his team are working to develop a two-zone combustion system - where EGR is maintained in a layer on the periphery of the cylinder, and the air-fuel mixture is maintained in the center of the cylinder. The required engine load, or current airflow as a percentage of peak airflow, determines the air-fuel zone's volume. EGR occupies the remaining space in the cylinder.



"Through the research we hope to come up with an intake system design and EGR system design that will create the two regions," Ramadan says. "This may influence design of flow ports, valves and valve timings. The most critical challenge is to minimize the mixing between the two zones for stable and complete combustion."

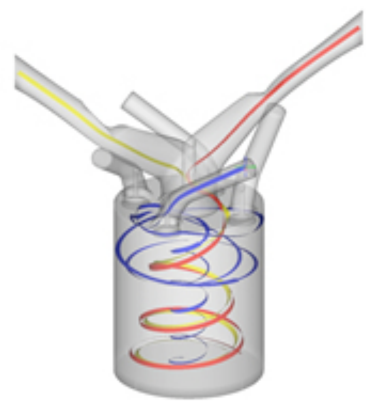
Ramadan's team uses KIVA-3V, a computational fluid dynamics (CFD) computer code for multidimensional combustion modeling, to perform three-dimensional transient calculations that simulate internal combustion engine processes. To maintain air in the center of the cylinder and EGR in the outer layer, air flows through a centrally located intake valve, while EGR flows through ports on the periphery of the cylinder. Placing EGR ports on opposing sides of the cylinder and implementing a helical intake system triggers a swirl motion that helps sustain stratification - or the formation of layers.

Researchers initiate the numerical simulations at the beginning of the intake stroke - when the piston of the cylinder is moving downward and the intake valve is open. The downward movement of the piston produces a vacuum effect in the cylinder, sucking air and fuel in through the center valve and EGR through the peripheral ports. The simulations continue through the compression stroke - where the upward motion of the piston compresses the air-fuel mixture and EGR.

For each simulation, parameters and engine conditions are implemented into the KIVA code, generating PostScript files of the detailed results. The group varies engine parameters - such as bore, stroke, squish, RPM, valve timings, and port geometry - during simulations to determine the best configuration for achieving stratification.

Visualizing the flow of gases

In the early stages of the project, researchers couldn't efficiently visualize plots or images generated from the results of the simulations because KIVA's postprocessor doesn't use a graphical user interface (GUI). An input text file was useful for generating a large number of hard copy plots, but the visualizations were not in color and were difficult to read and interpret.



The group heard about CEI's EnSight visualization software at a KIVA User's Conference and purchased a license to run on a Silicon Graphics Octane workstation. The software enables users to visualize, analyze and communicate CFD results.

"Using KIVA with EnSight allows us to generate results and visualize them in an efficient and useful format," Ramadan says. "We can tailor plots or animations to suit our own preferences and needs."

Now, the KIVA code performs the calculations and generates output files, which are converted by a KIVA translator to EnSight input files. EnSight then creates a model from the results. A typical model contains about 500,000 cells.

"On many occasions it's useful to visualize the 3D results as an animation," Ramadan says. "We can visualize results using particle traces or ribbons, for example, and plot streamlines."

Researchers are able to cut and slice anywhere in the model to generate contour plots or velocity vectors, and to modify colors, scaling, text or legends. They can also dive deep into the mesh to inspect regions in which errors are occurring.

"Due to valve and piston movement, the mesh might get distorted if it is not described correctly," Ramadan says. "EnSight helps us inspect the quality of the mesh and its reliability before we perform an expensive computer run to discover the error. It also helps us find the error when error messages don't provide clues."

The team uses EnSight's clip-part feature to evaluate the results by positioning clip planes to slice through the cylinder at different axial locations and crank angles. Contour plots are then generated to show the air and EGR distribution in the cylinder. The resulting visualizations display air in red and EGR in blue.

"By plotting the air and EGR contours in these clip planes, one can determine if the concentrations of EGR represent two zones or a single mixed zone," Ramadan says.

The jump to a physical prototype

After simulating several different designs, researchers established that two zones in a combustion system could be generated and maintained, but mixing would be difficult to control. Percentages depend largely on engine design, but generally those with four EGR ports showed the most promising results.

For one model, air mass fraction contours were plotted at the point where the piston bottoms out at the end of the intake stroke - called "bottom dead center," or BDC. Results showed a maximum concentration of air in the EGR layer of 10 percent, and a maximum concentration of EGR in the air layer of 30 percent.

"Some results look promising, but further work is needed to determine if the two regions will remain unmixed during the engine operating cycle," Ramadan says. Complete stratification would be ideal, he says, but maintaining partial stratification of about 80 percent during the compression stroke is acceptable. The project, which started in May 2003 and also involves studying different engine concepts and technologies, will last for a total of two years.

"If we are successful at creating a feasible design, then a prototype will be built and tested," Ramadan. "If the experimental results from the prototype confirm the simulation results, the engine could be used and tested in an actual vehicle."

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