
CD-adapco
INTERNAL COMBUSTION ENGINES
ICE

INTRODUCTION

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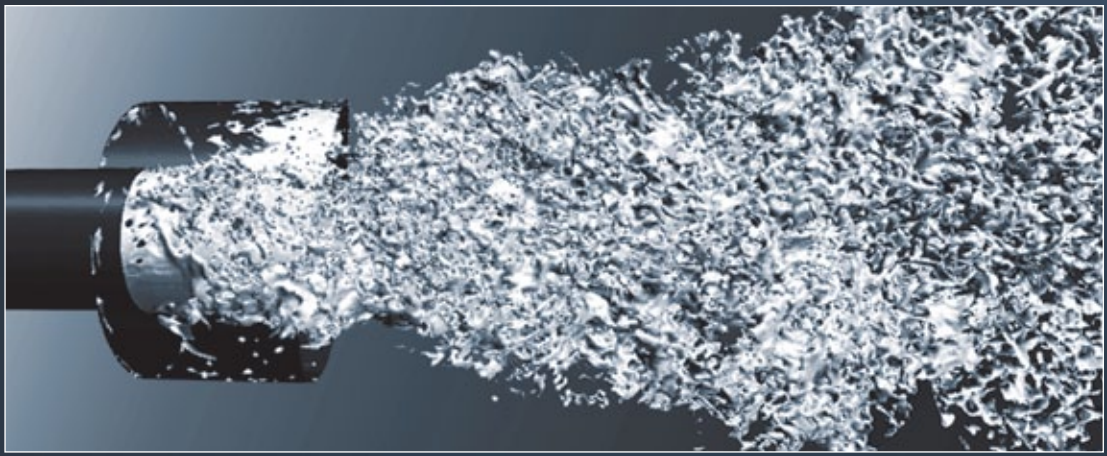


Designers of modern Internal Combustion engines face huge challenges to deliver power units which satisfy legislation and have competitive economy, performance and manufacturing cost. In particular, technology advances in fuel injection systems, alternative fuels, combustion systems, multi-fuel operation, downsizing and engine management coupled to ever shorter engine development timescales dictate that analysis is used widely to deliver optimum solutions.

Although CFD analysis of in-cylinder flow and combustion has been established for over 30 years, the demands for increasing accuracy, flexibility, speed of turnaround and closer integration of analysis into engine development programs have never been greater.

CD-adapco has been actively involved with in-cylinder analysis from its inception and there are many engines in production around the world today that have benefitted from detailed analysis using the STAR-CD/es-ice suite of software. These range from the smallest motorcycle through car and truck engines to the largest stationary and marine engines.

To keep pace with developments in engine technology, CD-adapco is continually developing the software to add new capabilities, functionality and the speed and ease with which powertrain engineers can execute projects.

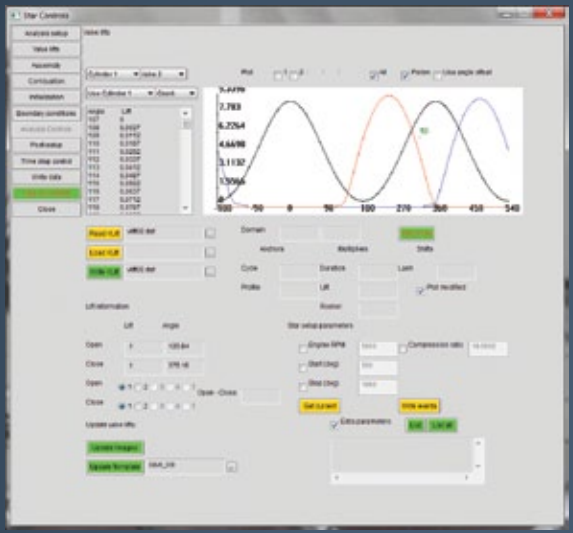
PRE & POST-PROCESSING

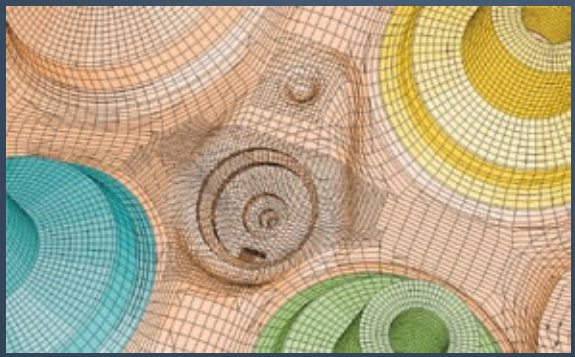
IC Engine in-cylinder analysis is particularly challenging in the respect that extremely complex physics occurs on short timescales and within a moving geometry.

To aid the setup of these calculations and visualization and interpretation of results, CD-adapco has developed a pre- and post-processing environment, es-ice, to complement the STAR-CD solver.

The pre-processor provides the user with all the tools necessary to generate computational meshes that accurately capture geometric details and to set up operating conditions and modeling choices including automatic template generation.

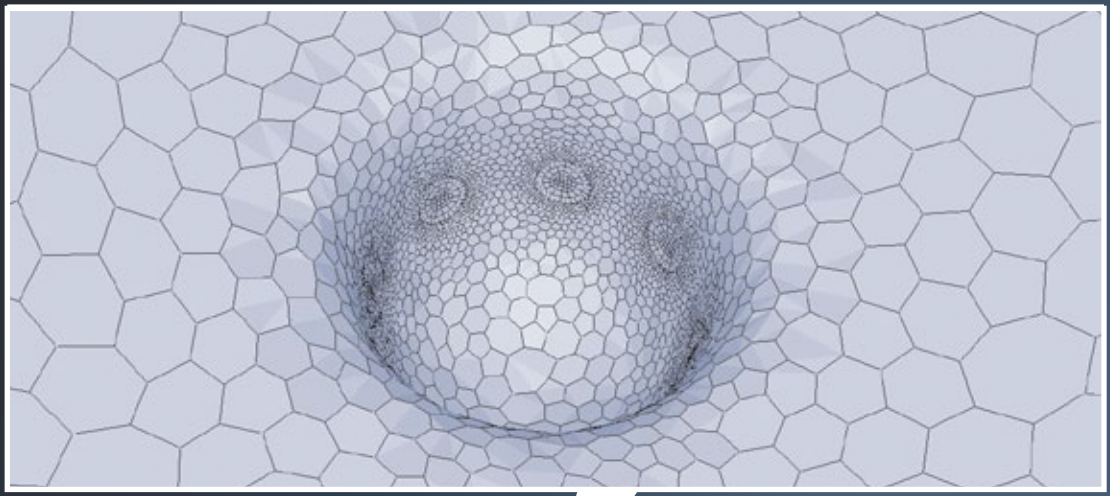
For example, the figure on the right shows the es-ice environment and a gasoline engine mesh where key geometric details in the ports and around the intake valves have been accurately captured using prism layers adjacent to the surface and local mesh refinement at the spark plug.

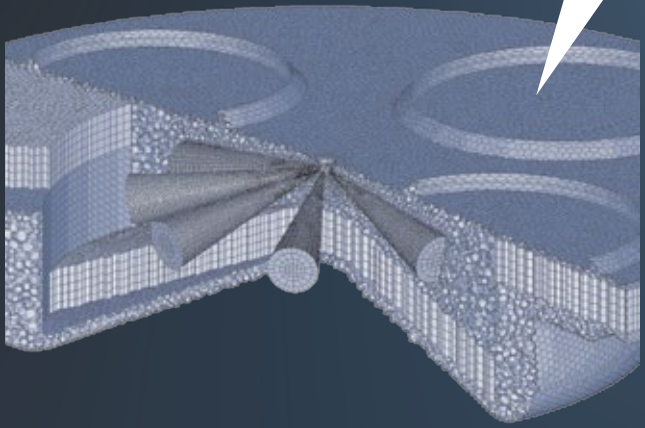




Accurate prism layer meshing and spark plug details captured by the dedicated es-ice pre-processing environment

PRE & POST-PROCESSING

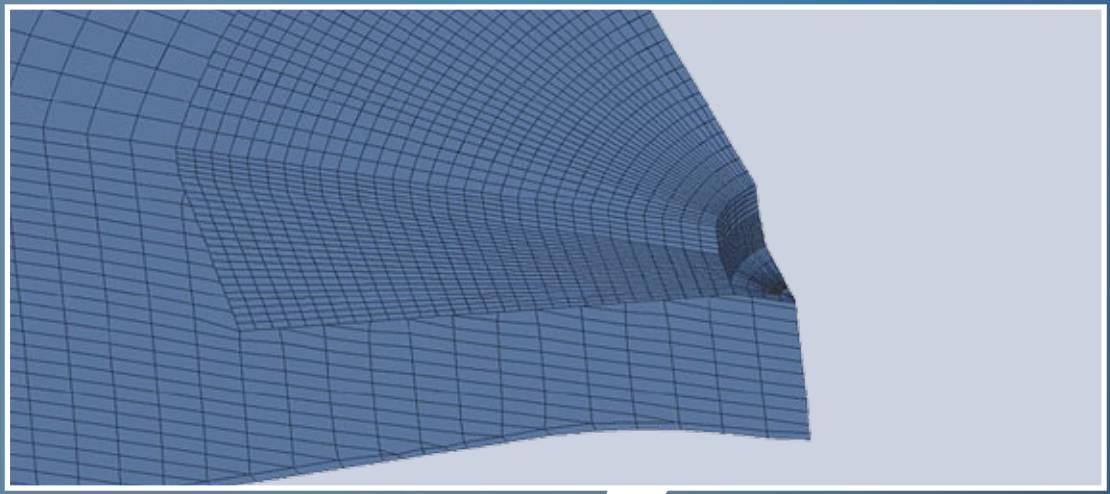


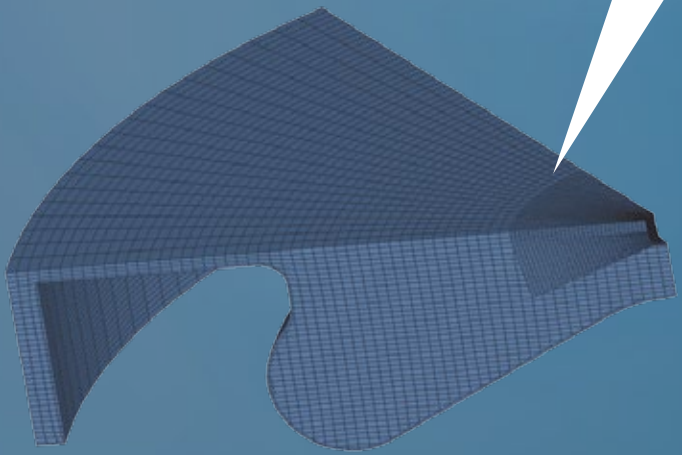


As the solution evolves, meshes appropriate to particular phenomena can be introduced by accurately mapping the solution at a prescribed time in the engine cycle.

The figure above shows a spray-aligned mesh introduced at the time of fuel injection and used to capture the high gradients and turbulent mixing that occurs within the spray.

PRE & POST-PROCESSING

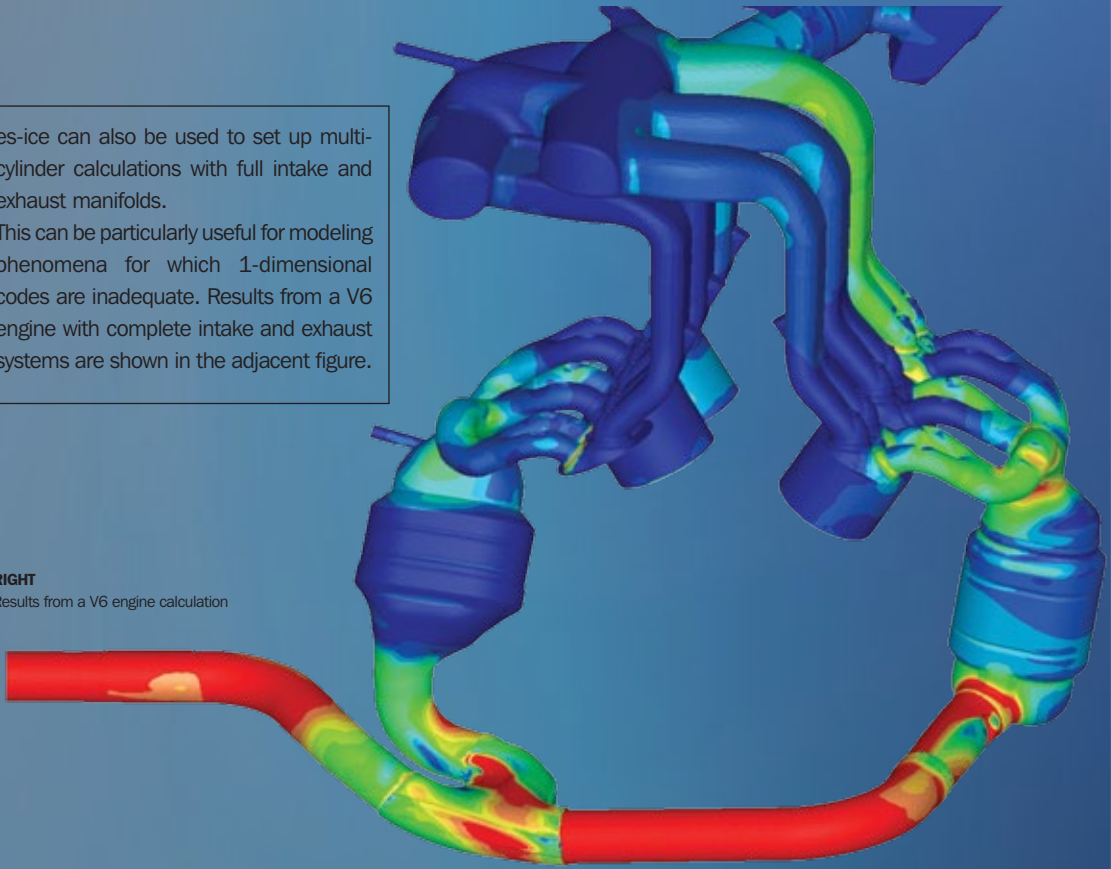




LEFT
Spray aligned meshes used to accurately model the fuel injection, spray evaporation and mixing processes

PRE & POST-PROCESSING

es-ice can also be used to set up multi-cylinder calculations with full intake and exhaust manifolds.
This can be particularly useful for modeling phenomena for which 1-dimensional codes are inadequate. Results from a V6 engine with complete intake and exhaust systems are shown in the adjacent figure.



RIGHT
Results from a V6 engine calculation

PHYSICS

The processes in IC Engines are extremely complex and include turbulence, heat transfer, 2-phase flow, evaporation and mixing, spray-wall impingement dynamics and films, chemistry and turbulence-chemistry interactions, real-gas effects, high-speed flow, radiation etc.

To be able to calculate these routinely, accurately and robustly is a significant challenge. STAR-CD has been developed over many years to incorporate appropriate models and develop Best Practices for simulating these phenomena and extensive comparison with experimental data has been made to give confidence that results are meaningful.

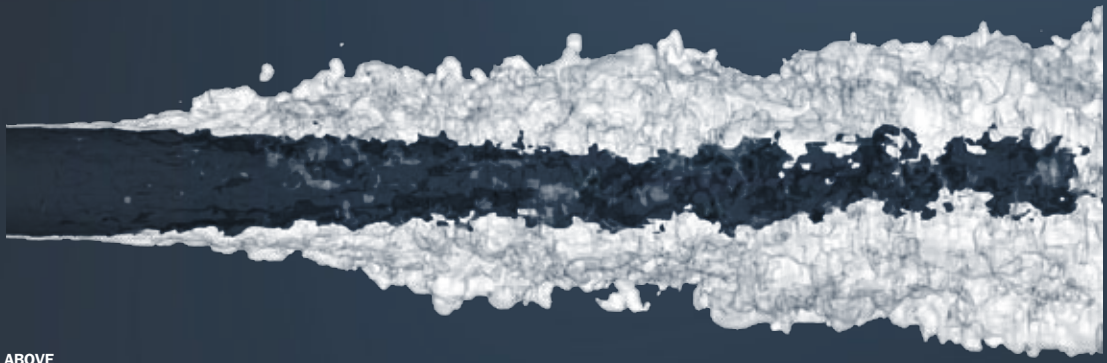
TURBULENCE MODELING

Turbulence directly affects all the in-cylinder processes and the modeling of turbulence and its effect on the flow, mixing, fuel evaporation and combustion are critical to engine performance.

Reynolds Averaged Navier Stokes (RANS) models are used predominately and appropriate modifications to standard k-ε and k-ω models are incorporated to account for compression-induced strain on the turbulence field, low Reynolds number effects and heat transfer.

ABOVE
Fuel injection during intake for a DI gasoline engine

SPRAY MODELING



ABOVE
Diesel spray breakup modeling using VOF and LES

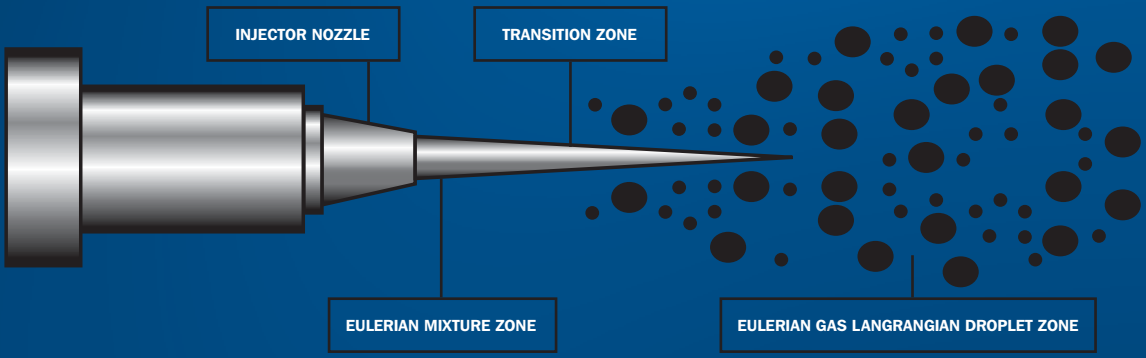
The Lagrangian or Discrete Droplet Model approach to spray modeling has been developed for more than 30 years and has been used successfully for many different types of injector, in both diesel and gasoline engines.

There has been tremendous evolution in fuel injection systems during this time, for example, common rail systems and multiple injections have become commonplace and injection pressures have increased by an order of magnitude; models in STAR-CD have also evolved to be able to model accurately the sprays produced by these systems.

The characteristics of the spray are strongly dependent upon the primary breakup process. This, in turn, is determined by nozzle geometry, the engine operating condition, fuel injection rate and fuel and gas properties.

Although STAR-CD contains a number of semi-empirical correlations to help in the determination of initial conditions for Lagrangian calculations – and these have been used successfully for many years – CD-adapco has also pursued two alternative routes to introduce more fidelity into resolving the in-nozzle flow and the breakup of the liquid jet.

SPRAY MODELING



ABOVE
The ELSA model used to predict spray primary breakup

The first of these approaches is the ELSA (Eulerian-Lagrangian Spray Atomization) model in which the flow inside and immediately downstream of the nozzle hole is modelled as a continuous Eulerian liquid phase. This is coupled to the Lagrangian model by introducing a transition region between the Eulerian and Lagrangian regimes in which the primary breakup process is modelled via an equation for liquid surface area density. In this way, the effects of nozzle design or injection and engine operating conditions can be seen immediately.

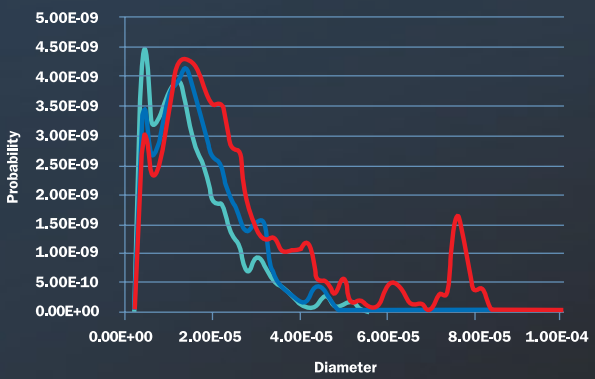
The model has shown excellent agreement when compared to rig-based experimental data over a wide range of operating conditions and for both non-evaporating and evaporating sprays and is now being used for in-cylinder spray and combustion simulation. The figure above shows the main principles of the method.

SPRAY MODELING

ABOVE & RIGHT
LES/VOF calculation of the spray primary breakup process used to calculate initial conditions for a Lagrangian model

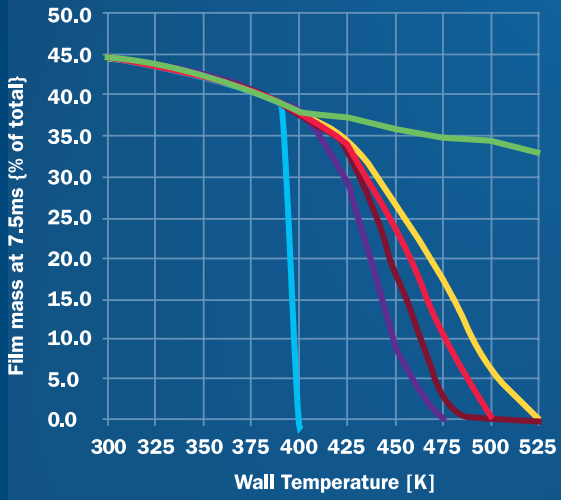
An even more detailed and fundamental approach is to compute the in-nozzle flow and primary breakup processes using a method based on Volume-of-Fluid (VOF) and Large Eddy Simulation (LES). In principle, this technique models all of the turbulent scales that are important for disruption and breakup of the continuous liquid phase and is thereby able to directly calculate rather than model the primary breakup process itself.

By continuously capturing information about the size, velocity, position etc. of all the "blobs" of fluid generated from the liquid core, statistics of size and velocity can be assembled in a similar fashion to the way in which this would be done experimentally. The raw information can also be conditionally sampled, for example based on position, offering a comprehensive approach to providing the initial conditions for a Lagrangian calculation based on nozzle design.

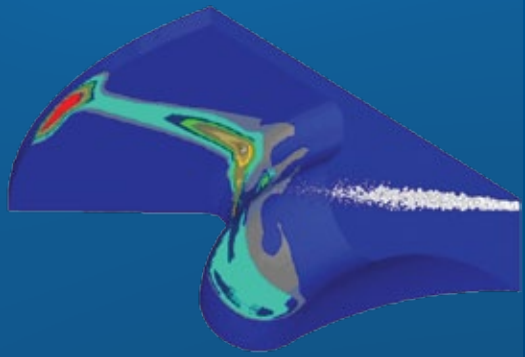


ABOVE
Calculated distribution of droplet sizes.

SPRAY MODELING



ABOVE
Effect of surface temperature on wall film evaporation rate between saturation temperature and the Leidenfrost temperature

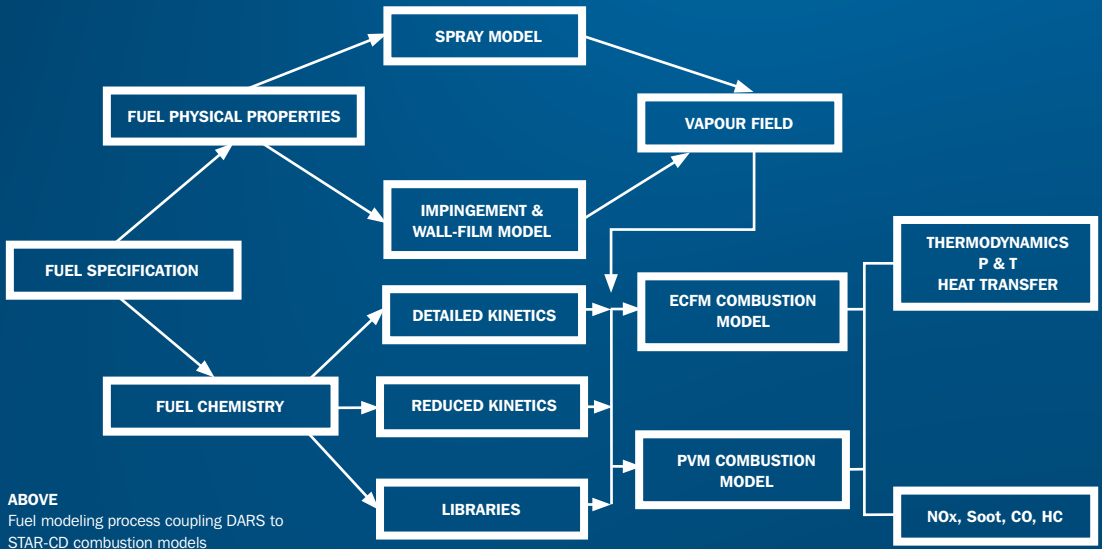


ABOVE
Wall film in a DI Diesel Engine

Increasing injection pressures coupled with higher thermal loading have also resulted in impingement regimes where the surface temperature is above the liquid saturation temperature. New modeling has been introduced into STAR-CD to give more realistic behaviour under these high temperature conditions up to and beyond the Leidenfrost temperature.

Although general multicomponent modeling of evaporation has been available in STAR-CD for many years, more recently, 2-component fuel mixtures such as E10 (10% ethanol, 90% gasoline) or B30 (30% biodiesel, 70% diesel) have come into prominence and the evaporation and mixing of these is modeled correctly to yield a vapour field that can be used directly by the ECFM and PVM combustion models.

COMBUSTION & REAL FUELS



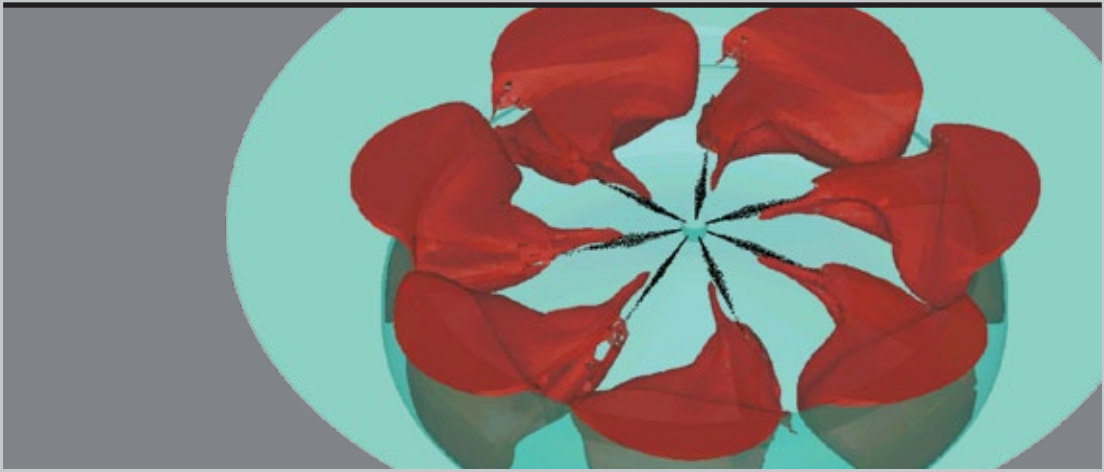
ABOVE
Fuel modeling process coupling DARS to STAR-CD combustion models

Fuels and the detailed modeling of fuel chemistry have become increasingly important for a number of reasons: the usage of "E" and "B" fuel mixtures for ground transportation is growing throughout the world; there are huge reserves of natural gas and their low emissions characteristics make them ideal candidates for power generation and inshore marine applications and, last but not least, the requirement for ever increasing accuracy of combustion modeling and, in particular, emissions prediction dictates detailed chemistry is used to represent the fuel.

To address this, CD-adapco and DigAnaRS have introduced generalized detailed chemistry in which chemistry mechanisms developed in the DARS chemistry modeling software can be used in the combustion models in STAR-CD.

This has the clear advantage of combining detailed chemistry within the framework of combustion models that explicitly recognize flame structure and turbulence-chemistry interactions and which have been subjected to extensive validation.

COMBUSTION & REAL FUELS



ABOVE
Diesel combustion simulated with the ELSA and ECFM-CLEH models

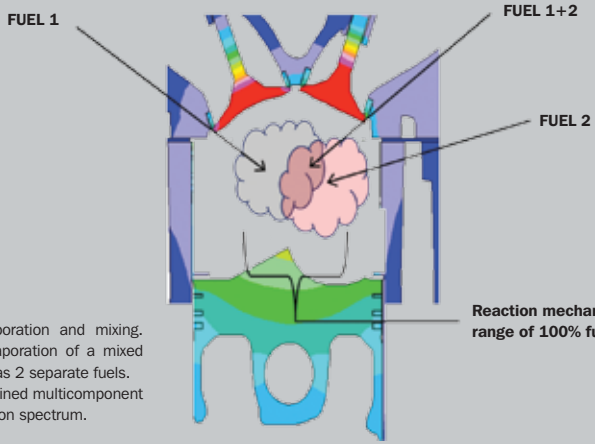
Depending on the combustion model being used, both library-based and on-the-fly chemistry using either detailed or reduced mechanisms are utilised. Cell-clustering techniques are available to reduce computation time for users that wish to solve chemistry on a cell-by-cell basis. A major advantage of using library-based methods is that the complex chemistry is performed just once for each fuel and thereafter used as a multidimensional look-up table, substantially reducing run time.

In collaboration with DigAnaRS, usage of detailed chemistry mechanisms and libraries for an ever-increasing range of fuels are available using a DARS fuel licence or, for users wishing to use their own chemistry mechanisms, DARS can be used directly to generate all information required for the supported combustion models.

The ECFM (Extended Coherent Flamelet Model) family of models has been widely used to simulate diesel, gasoline, and gaseous fuelled engines operating under premixed, diffusion and homogeneous autoignited combustion regimes.

The model can be used with in-built libraries for diesel or gasoline or with more extensive fuel mechanisms generated using DARS. In addition to the main combustion event, NOx and soot emissions can be calculated over a wide range of operating parameters, including high levels of EGR.

COMBUSTION & REAL FUELS



RIGHT
Schematic of 2-component evaporation and mixing. Components may result from evaporation of a mixed fuel, e.g. E10, B20 or introduced as 2 separate fuels. Chemistry mechanism of the combined multicomponent mixture accounts for full composition spectrum.

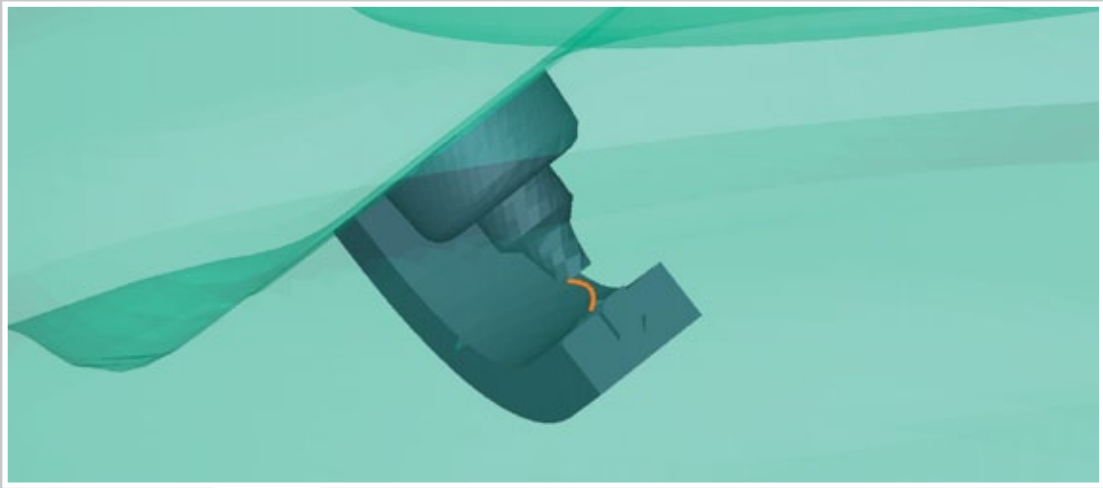
A more recent development of this model is the ECFM-CLEH (Combustion Limited by Equilibrium) model which offers advantages in its treatment of diffusion flames. Experience with this model, coupled to the ELSA spray model, indicates improved predictions of diesel engine combustion over a wide range of operating conditions.

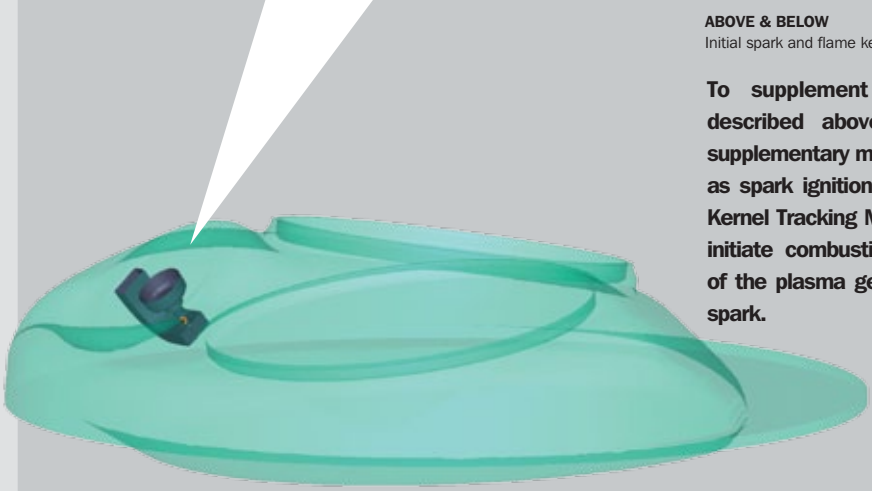
In addition to the ECFM family of models, STAR-CD also incorporates a Progress Variable Model (PVM) which combines the level-set method (also referred to as the g-equation) and the Transient Interactive Flamelet (DARS-TIF) model for post-flame chemistry. Combining models in this way has removed the restriction to specify premixed or diffusion modes of combustion and both can co-exist in the same simulation.

Both the ECFM-3Z and PVM models offer the possibility of modeling the combustion process as a 2-component mixture, as mentioned earlier. Here, the models allow a chemistry mechanism that correctly represents 100% of component 1 to 100% of component 2.

This situation may exist if the evaporation characteristics of the 2 components are widely different or in dual-fuel engines where the fuels are introduced separately, such as in gas engines operating with a diesel pilot injection. Either (or both) of the components can itself be a complex fuel molecule, for example combustion involving both diesel and gasoline simultaneously can be accommodated using the model.

INTERNAL COMBUSTION ENGINES

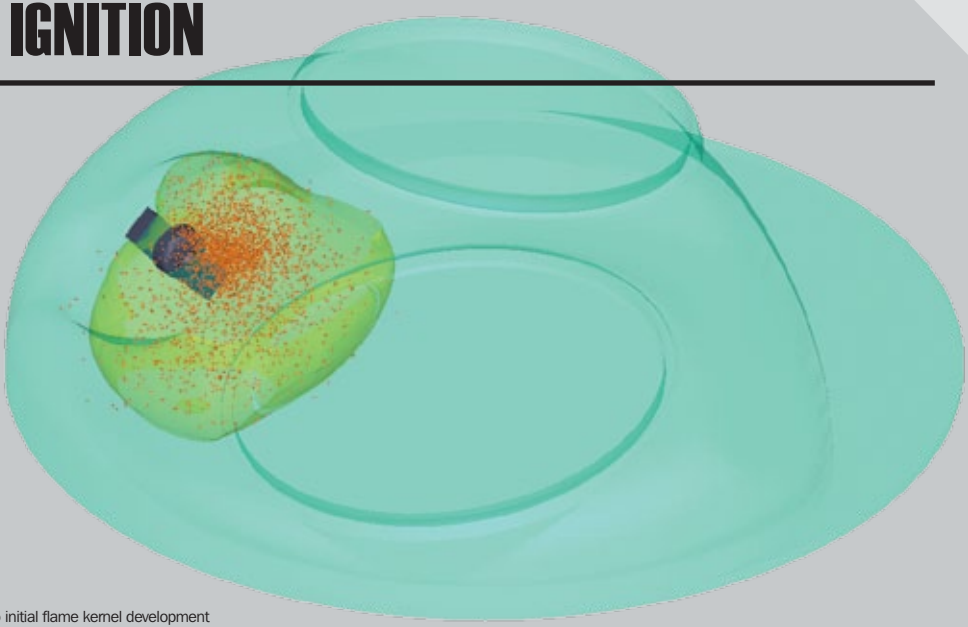




ABOVE & BELOW
Initial spark and flame kernel development using the AKTIM model

To supplement the combustion models described above, STAR-CD also contains supplementary models for key processes such as spark ignition. The AKTIM (Arc and Flame Kernel Tracking Model) model can be used to initiate combustion by including the effects of the plasma generated by the high voltage spark.

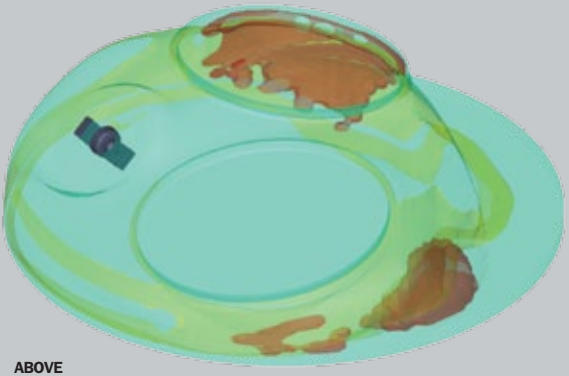
SPARK IGNITION



ABOVE
Transition from plasma to initial flame kernel development

Here, the secondary (high voltage) circuit of the ignition system is included and a Lagrangian method is used to initiate and track a series of particles of high energy gas used to represent the plasma between the spark plug electrodes. The interaction of these particles with the gas and the transfer of their energy to the Eulerian gas phase initiates the flame kernel.

As AKTIM provides a model rather than a prescription of ignition, this has the advantage that phenomena such as misfire caused by low spark energy, large spark gap or high gas velocity at the electrodes can be simulated.

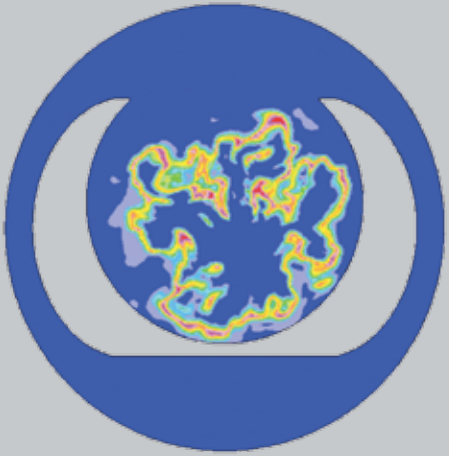


ABOVE
Flame propagation which later results in autoignition (knock) ahead of the flame in the unburned gas

RESEARCH

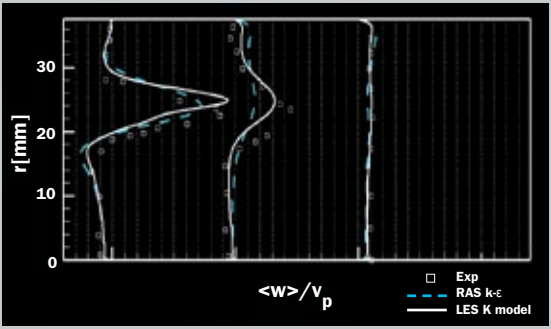
In addition to extensive in-house development and validation of new models, CD-adapco supports research at many universities and IC engine research programs throughout the world.

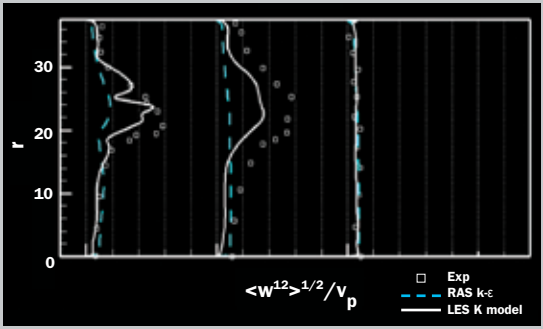
One research area that is particularly important is in-cylinder LES because it potentially offers a better description of the turbulence and a route to understanding and quantifying cycle-to-cycle variations. A number of universities around the world are using the LES/DES models available in STAR-CD to simulate motored engine flows and, more recently, combustion using the ECFM-LES combustion model.



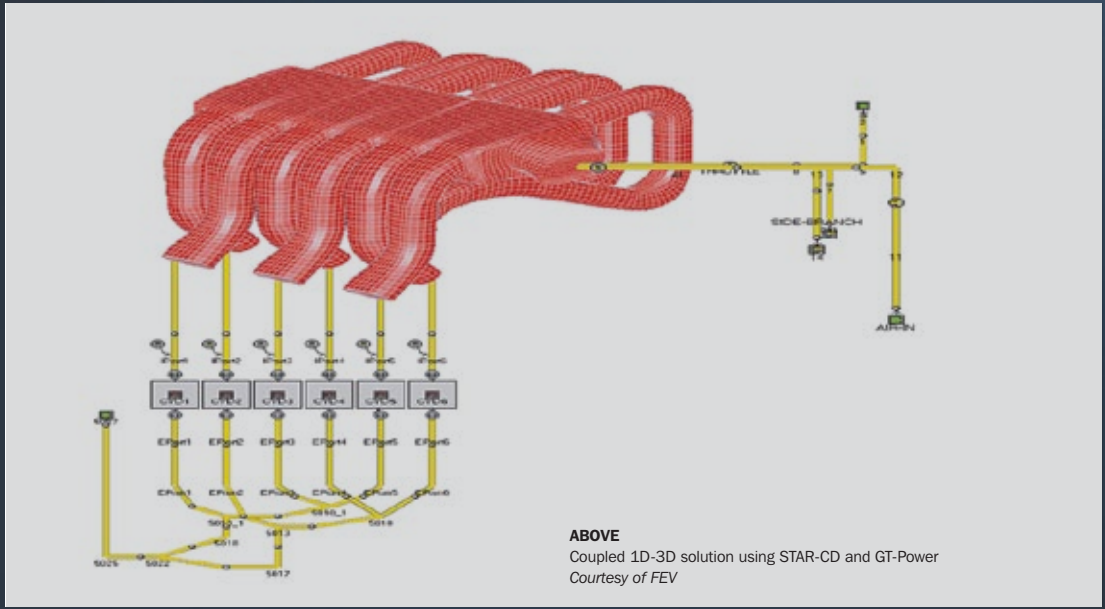
ABOVE
Combustion using the ECFM-LES combustion model
Courtesy of Prof Fontanesi, University of Modena

BELOW
Comparison of Mean and RMS turbulence profiles in a motored model engine indicating improved predictions using the LES model in STAR-CD compared to RANS
Courtesy of Prof Dan Haworth, Penn State University





COUPLING TO 3RD PARTY SOFTWARE



ABOVE
Coupled 1D-3D solution using STAR-CD and GT-Power
Courtesy of FEV

In addition to providing a comprehensive in-cylinder solution, es-ice and STAR-CD can also interact with 3rd party software to provide a 3D model embedded within a 1-dimensional engine simulation code, such as GT-Power or WAVE, and also to derive cycle averaged boundary conditions as input to a thermal calculation of the engine structure, for example using STAR-CCM+, which can also accurately account for the coolant flow, or Abaqus.

The main advantage of coupling to 1-dimensional codes at the time-step level is that there is a simultaneous interaction between the 1D and 3D solutions and this allows the complete system model with dynamic effects in the intake and exhaust systems, interactions between cylinders etc. to be accounted for accurately in the STAR-CD model.

COUPLING TO 3RD PARTY SOFTWARE

Typical applications include: unsteady boundary conditions for intake calculations of 4-stroke engines; EGR mixing; scavenging of 2-stroke engines and other instances where combined detailed and system level models are needed to deliver the level of fidelity required.

Derivation of spatially-varying cycle-averaged heat transfer boundary conditions is a prerequisite for making accurate calculations of structural temperature. Here, the focus is not the fluctuation of surface temperature that occurs during the engine cycle but rather the steady-state or more slowly varying thermal transients that affect the entire structure.

Averaging of the instantaneous local heat-transfer coefficient and gas temperature determined by the STAR-CD solution is calculated as a post-processing operation and this can then be mapped to the structural model, thereby allowing for spatial variations within the cylinder, that occur during the entire engine cycle, to be represented correctly in the 3D solution of structural temperature.

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To keep pace with developments in engine technology, CD-adapco is continually developing the software to add new capabilities, functionality and the speed and ease with which powertrain engineers can execute projects.

ICE EVENTS

CD-adapco hosts specific IC Engine workshops every year in the US, Europe, Japan and Korea. Users of our software are invited to attend these events at which the latest technical developments are discussed, and users have the opportunity to present their own work.

CD-adapco strongly supports academic use of its products and universities around the world are encouraged to use our simulation software in academic programs.

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