ADVANCES IN COMBUSTION MODELING IN STAR-CD: a new technique for automatic grid and mesh motion generation applied to Diesel combustion and Emissions analysis

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ABSTRACT

The ECFM CLE-H is a new approach developed by CORIA [1] [2], [3] to simulate the different phases of Diesel combustion: auto-ignition, premixed and diffusion flame burning. The original proposal was based on two modelling for the two flame structures: premixed and diffusion flame. Particular emphasis was put on improving modelling for the diffusion combustion. The combustion model split the flame front in three zones: non-reactive zone, premixed zone and un-premixed zone. For each zone, a specific combustion model is attached based on flame structure analysis. CLE-H stands for Combustion Limited by Equilibrium Enthalpy; model uses an equilibrium fuel mass fraction to compute the average heat release rate. This equilibrium fuel mass fraction has been calculated a priori from complex chemistry calculations for fuel to limit burning rates. A presumed Beta-shape PDF is adopted to average the equilibrium at equilibrium. Auto-ignition is modelled from tabulated fully detailed chemistry. The tabulation strategy TKI proposed by IFP [4] is used. This model was completed with a soot model. This soot model is based from look up table established from a detailed chemistry mechanism and an original sectional method. The complete model is implemented in Version 4 of STAR-CD allowing a very high flexibility in meshing including general polyhedral cells. This new technique fully automates the simulation process and preserves a high mesh quality during the grid motion. A detailed validation was carried out on the base of a wide range of test results.

ECFM CLE-H MODEL DESCRIPTION

Flame front description

The approach ECFM CLE-H proposes to substitute the original model for burnt gas developed in ECFM-3Z by two sub-models elaborated on both the description of the premixed flame (ECFM formulation) and the diffusion flame (CLE-H formulation).

ECFM: Extended Coherent Flame Model
CLE-H: Combustion limited by thermodynamic equilibrium

Thus, the flame front in each cell is split into three zones (Figure 1):

- Passive mixing zone
- Premixed flame zone
- Diffusion flame zone

INTRODUCTION

A three-step process governs the combustion from direct injection, gasoline and diesel: ignition, premixed flame and diffusion flame. The weight of the fuel consumption by one or another flame structure depends strongly on the injection timing. Thus, for example, in HCCI combustion, most of fuel is consumed during the auto-ignition phase. ECFM CLE-H model is based on ECFM formula developed by EM2C [5] and ECFM-3Z model developed by IFP [5] and currently used at Renault in STAR-CD. These modifications were motivated by the implementation of a diffusion flame description. In the case of classical combustion, close to TDC, most of the energy flux comes from the diffusion flame.

This approach was developed by CORIA. The implementation was done by CD-adapco in version 4 of STAR-CD. STAR-CD Version 4 allows a very high flexibility in meshing including general polyhedral cells. This new technique fully automates the simulation process and preserves a high mesh quality during the grid motion. A detailed validation was carried out on the base of a wide range of test results.
The couple \((\vec{Z}, \vec{Y})\) governs each zone. A transport equation is used to determine the value of the couple.

The formalism \(\vec{Z}\) refers to Favre mean value for the mixing variable and \(\vec{Y}\) refers to the mean value for the associated reactive scalar.

The formalism and detailed mathematical description of ECFM CLE-H can be found in reference [1] and [2]

**NO EMISSIONS:**

The major development in ECFM-CLEH is related to refined description of the simultaneous premixed and diffusion combustion. Two different progress variables are derived for each mode of combustion. These variables are 'c' for the premixed combustion and 'alpha' for the diffusion. Therefore, all species and especially the emissions will contain two different source terms. Formally, the equation below is an example for NO formation.

\[
\tilde{\omega}_{NO} = c \tilde{\omega}_{NO} \bigg|_{PM} + c \alpha \tilde{\omega}_{NO} \bigg|_{DIFF}
\]

**SOLUTION METHODOLOGY**

All of the widely used codes for Internal Combustion Engine simulation employ the Finite Volume Methodology (FVM). A step in this direction was to introduce a Generalised Finite Volume Method for Unstructured Meshes to Arbitrary Deformable Polyhedral in version 4 of STAR-CD

The control volume defined by the coordinates of its vertices can have an arbitrary number of cell-faces (Figure 4).

This greater flexibility is available in the STAR-CD Version 4 codes including the options of arbitrary polyhedral cells (Figure 4); allow a fully automated process from the CAD definition to the final mesh motion, and therefore reducing the simulation process to model set-up, computing and post processing as shown in figure 5.

**Figure 4 Control volume of an arbitrary polyhedral shape**

**Figure 5: Elements of simulation process**

**Figure 6: Traditional mesh (left) and new trimmed mesh using polyhedral cells (right)**
It should be noted that while this new technique introduces a great flexibility reduces drastically the mesh and mesh motion generation as indicated in figure 5, even for very complex geometry like shown in figure 7, the technique preserves a higher quality grid as shown in figure 6.

Figure 7: Typical full three dimensional mesh using the polyhedral trimmed technique

**DI ENGINE: MODEL VERIFICATION**

The combustion in DI engine and especially under full load conditions exhibits the three mode of combustion: Auto-ignition, propagation and diffusion. Therefore, the emissions history will strongly depend on the combustion mode depending on the different progress of the combustion.

**THE ENGINE CONFIGURATION**

The computed configuration is a typical 2 liters DI Engine-4 cylinders, under production. The symmetry of the geometry, the relative position of the injector into the combustion chamber and the nature of the swirling flow at Intake Valve Closing make the choice of a sector mesh good enough for this evaluation. The geometry and the mesh are shown in figure 8.

Figure 8: Typical mesh used for combustion

**MODEL VALIDATION**

Full load validation was done in different engine configurations, not communicable. Combustion evolution through CA variables and IMEP value were compared with the measurements.

We have used two different engines quite different in term of bowl design, initial swirl as well as injector nozzle diameter.

Figure 9: Predicted and measured Pressure history fro ENGINE A (Normalized quantities)
The computed and measured in-cylinder pressures and corresponding rate of heat release are represented on figures 9, 10, 11 and 12 for two engines operating at full load.

The overall agreement is rather good including the combustion history indicating that the model is very well capturing the premix phase and the diffusion phase.

**PART LOAD AND OTHER OPERATING CONDITION**

A series of another different operating conditions including EGR variation from 0% to 50% was executed for a partial load validation. As a result, the IMEP measurements have been compared to the calculated ones. This is shown in figure 13 and figure 14 in which almost all predicted values are within the range of 2% of error.
NOx results from calculation for the two engines and for all operating condition investigated in the work are summarized in figure 15. The values reported in figure 15 are ppm and the predicted values are directly compared to the measured ones. One can see in figure 15 the excellent trends obtained, the maximum error is about 20%.

CONCLUSION

The ECFM CLE-H combustion model has been applied in car engines for validation of Diesel applications. The combustion was based on a calculation of the progress variable including equilibrium information. The distribution in the diffusion flame was simulated by Pdf, function beta approach. This approach was coupled to premixed flame simulation based on ECFM model. Comparisons on IMEP level and the different combustion characteristic angles show a good agreement with experimental data. A significant breakthrough was reached in term of CPU saving. The using of look-up tables for all chemistry description, including pollutants, improved the numerical stability significantly and made the increase of the time step possible.

The model is implemented into the solution methodology of the latest developed version 4 of STAR-CD. This solution methodology offers a very high flexibility in meshing including arbitrary polyhedral cells. This technique applied to very complicated three-dimensional I.C.E geometry reduces drastically the user time and preserve a very high grid quality for the finite volume solution.

Future works will be devoted to finish validation of a new soot model coupled to ECFM CLE-H and continue to couple a CO and UHC formation model. Validation and testing will be carried out for gasoline direct injection, and port fuel injection SI Engine configuration.

REFERENCES

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