Modelling of lean turbulent burning in SI engines

1. Background

Burning of homogeneous lean fuel-air mixtures in a SI engine is considered to be a promising technological solution aimed at decreasing fuel consumption, reducing hydrocarbon and NO_x emissions, and improving combustion efficiency. However, to implement the lean combustion concept using the homogeneous burning mode, several problems should be resolved, e.g. poor ignitability of very lean mixtures, cyclic variabilities due to slow growth of the initial lean flame kernel, severe knock tendency at high loads due to slow flame propagation, etc. To resolve these problems and to realize the high potential of the homogeneous lean combustion concept, the automotive industry has a significant need for advanced, predictive, efficient, and robust CFD tools that can be used to numerically investigate ignition, initial flame kernel growth, and turbulent burning of the lean charge, as well as pollutant formation in the combustion chamber of a SI engine. Accordingly, at the present stage, the focus of the project is placed on development and validation of advanced, high fidelity, and numerically efficient models of (i) turbulent combustion of lean mixtures of fossil and renewable fuels and (ii) NO_x emissions from SI engines.

From combustion modelling side, the following major challenges are associated with lean burning. First, lean flames are characterized by a low laminar flame speed and a large laminar flame thickness. Accordingly, such flames are characterized by a low Damköhler number Da and a high Karlovitz number Ka. However, among various regimes of premixed turbulent combustion, the regime of $Da < 1$ and $Ka \gg 1$ is least understood. In this regime, governing physical mechanisms of the influence of turbulence on premixed combustion have not yet been identified and advanced predictive numerical models have not yet been developed.

Second, the influence of flame chemistry on turbulent burning rate is of more importance in lean mixtures subject eventually to local combustion quenching. Therefore, advanced models, which take into account not only global laminar flame characteristics such as its speed and thickness, but also complex or, at least, reduced chemistry of combustion of various (fossil and renewable) fuels, are highly required for research into lean burning in and emissions from SI engines.

2. Research methods

As far as premixed combustion at $Da < 1$ and $Ka \gg 1$ is concerned, relevant advanced Direct Numerical Simulation (DNS) runs are ongoing in the University of Lund and these DNS data are jointly analysed by us and colleagues from Lund to develop new high-fidelity models.

As far as chemistry of lean premixed turbulent combustion is concerned, a typical approach to modelling it consists in invoking a presumed Probability Density Function (PDF) of combustion progress variable c (normalized mass fraction of the deficient reactant) in order to average rates $W(c)$ of production or consumption of various species. However, a standard presumed PDF approach is fundamentally flawed, because such a PDF is commonly modelled using quantities that are controlled by probabilities of finding unburned reactants and burned products, but are weakly affected by the probability of finding reaction zones. On the contrary, it is the latter probability that controls mean reaction rates $\overline{W(c)}$.

To resolve the problem, a modified presumed PDF method was recently put forward by us. In order to validate and further develop this new approach, data obtained in complex-chemistry DNSs are necessary. Two such DNS databases generated in University of Cambridge, UK, and Indian Institute of Science, Bangalore, were recently transferred to Chalmers. Within the framework of the project, the DNS databases will be analysed to assess the newly modified presumed PDF approach.

3. Results

Recently, Prof. Sabelnikov (ONERA, France) jointly with our group developed a new theory of turbulent combustion at $Da < 1$ and $Ka \gg 1$. The theory yields a simple analytical equation for the turbulent burning velocity under such conditions and this prediction, see black dashed straight line in Fig. 1a, agrees very well with the aforementioned Lund DNS data, see red circles.

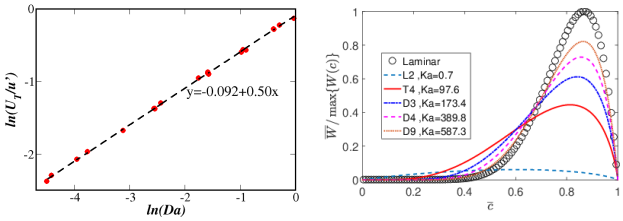

Figure 1: (a) Validation of the theory against Lund DNS data. (b) Dependencies of the normalized mean reaction rate on the mean combustion progress variable.

Moreover, analysis of those DNS data shows that the dependencies of the mean normalized reaction rate $\overline{W}$ on the mean combustion progress variable $\bar{c}$, computed at high Ka, see red, blue, magenta, and orange lines in Fig. 1b, differ significantly from such dependencies obtained from low-Ka flames, see cyan dashed line, but tend to the laminar-flame dependencies, see black circles, when Ka is increased. This result implies that modelling of the effect of turbulence on mean reaction rates can be strongly simplified at high Ka by assuming that $\overline{W(c)} = W(\bar{c})$.

4. Conclusions and outlook

A new theory of turbulent combustion at $Da < 1$ and $Ka \gg 1$ is developed and validated against DNS data obtained in wide ranges of $Da < 1$ and $Ka \gg 1$.

As the next step, we plan to assess and further develop the newly modified presumed PDF approach by analysing the advanced complex-chemistry DNS data transferred by the leading research groups to Chalmers recently.