Fuel injection from subcritical to supercritical P-T conditions: a unified methodology for coupled in-nozzle flow, atomisation and air-fuel mixing processes

Reporting

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Summary of the context and overall objectives of the project
Fossil fuel consumption is expected to increase by over 20% over the next 3 decades in order to meet the increasing demand for infrastructure, trade and transportation. Development of engines complying with the forthcoming 2020 emission legislations, relies on the effective design of advanced high-pressure fuel injection systems and represents a key industrial priority. Such advanced injection systems can improve internal combustion engine performance in the following ways:
- Formation of high velocity fuel jets that lead to finer atomization and better air/fuel mixing.
- Increase of engine efficiency.
- Decrease of cavitation side effects, reduction of erosion damage and improvement of injector reliability.
- Reduction of soot and CO2 emissions.

The objectives of the present project involve the study of high pressure fuel systems injecting fuel at high temperature and pressure conditions, relevant to Diesel engines. The project involved experiments (outgoing phase at Sandia National Laboratories) and simulations (return phase) to study the phenomena occurring during fuel injection and how they can be exploited to improve engine design.

In particular, the following objectives have been achieved, each corresponding to the respective work package of the project:
(1) advanced thermodynamic models have been developed for describing fuel properties at extreme conditions. These models are demonstrated to accurately describe the thermodynamic and transport properties of Diesel surrogates/fuels and are superior to the current state of the art.
(2) novel experiments have been performed at Sandia National Laboratories (SNL), involving quantification of spray characteristics. Additionally, new techniques have been developed for in-nozzle diagnostics.
(3) numerical tools have been developed to predict the coupled in-nozzle flow and spray, using the developed models of objective (1) above. These tools are capable of describing all the relevant physical mechanisms during diesel fuel injection, with less ad-hoc assumptions of existing models.
(4) the aforementioned numerical tools have been validated and adapted to industrial cases, involving real-world complexities. Additionally, having in mind the application of said tools to an industrial setting, where fast, but accurate calculations are required, novel Machine Learning methods have been developed for predicting spray characteristics.
(5) the Researcher’s skills have been greatly expanded, as the project enabled him to undergo a wide variety of activities, ranging from hands-on experiments at high-end facilities around the world (at Sandia National Laboratories, Argonne National Laboratory, Paul Scherrer Institut), broadening his knowledge on thermodynamics and numerical methods and finally disseminating important findings through the participation in conferences and workshops and publications in journals.

Work performed from the beginning of the project to the end of the period covered by the report and main results achieved so far

The work performed in the frame of the project can be split into two main categories: the first category involves the development of models, integration within simulation tools, their validation and expansion to industrial context. The second category involves experimental procedures and diagnostics applied...
to both in-nozzle flow and fuel sprays.

Concerning the first category, an advanced numerical methodology for handling (Diesel) fuel sprays at elevated temperatures and pressures has been developed. This methodology involves the following key components:

(1) thermodynamic property modelling, including non-ideal effects that occur at the extreme conditions of modern fuel injection systems. This modelling involves Equations of State to accurately predict thermodynamic and transport property variation and consequent thermodynamic effects. The advancement described here is critical in further development of accurate tools for next generation engines.

(2) The developed thermodynamic models have been combined with numerical tools to simulate coupled in-nozzle flow and spray dynamics. This aspect allows to investigate conditions which depart from the classical atomisation theory, avoiding many of its shortcomings and pitfalls.

(3) The aforementioned tool has been extensively tested at various cases examined by the Engine Combustion Network (ECN), aiming to capture critical quantities of interest for the design of modern and next-generation Internal Combustion Engines.

(4) the last aspect of the numerical tool development was the accommodation of industrial requirements, involving realistic injection geometries/conditions and quick execution of the numerical tool, so that it will be practical in an industrial setting.

Concerning the second category, involving experiments for fuel studies, several novelties have been pursued:

(1) one refers to the use of various diagnostics for examining gasoline-like fuels at standardised conditions.

(2) the second refers to the development of a 3d tomographic reconstruction technique, that is capable of producing 3D volumetric distribution of fuel sprays.

(3) the third refers to the visualisation of internal flow in fuel injector orifices.

The importance of the aforementioned experimental methodologies and investigations is paramount; these diagnostics are capable of providing quantitative information of sprays to drive future developments in the field of alternative/synthetic/renewable fuels.

Important findings of the work performed have been published in seven peer-reviewed journals, one invited publication to a scientific bulletin and five international, scientific workshops/conferences. Furthermore, the outcomes of this work has been utilised as basis in the frame of new European projects: (a) one Innovative Training Network (ITN) project, aiming to train young researchers in designing next-generation engines, (b) one Global Fellowship (GF) aiming to train a young post-doctoral researcher on alternative/renewable/synthetic fuels. Finally, the developed models have been used by two Fuel Injection Equipment (FIE) industries for investigations and optimisation of their designs.

Progress beyond the state of the art and expected potential impact (including the socio-economic impact and the wider societal implications of the project so far)
The present program advanced the state of the art both through numerical simulation tools and experimental techniques.

The advancements in simulation tools offer a better understanding of spray characteristics, by including accurately thermodynamic property variations and induced effects. The inputs needed for thermodynamic modelling are based on the molecular characteristics of the fuel, providing a versatile tool for examining "what-if" scenarios, which can be exploited in design studies in fuel and automotive industries.

The fuel studies on gasoline-based blends is closely associated with the standardisation of fuels, investigation of fuel surrogates and composition on spray characteristics, relevant to different engine operating conditions, which subsequently affect emissions and performance.

Hence this work is a direct advancement in the quest of efficient, less polluting engines, either diesel or gasoline. However, on the more fundamental level, the diagnostics developed and used are relevant to the understanding of sprays (volumetric distribution of liquid, probability density functions of droplet sizes), relevant even to biomedical applications.

Dodecane mass fraction distribution of high temperature/high pressure planar dodecane spray.
Vortical structures during dodecane injection in nitrogen, ECN Spray-A conditions.
3D Rendering of diesel fuel injection, showing turbulent structures formed around the fuel jet.

3D Rendering of diesel fuel injection, showing the fuel plumes emerging from the injector.
Vortical structures during dodecane injection in nitrogen, ECN Spray-A conditions.

Temperature distribution of high temperature/high pressure planar dodecane spray.

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