3rd International Workshop of the Engine Combustion Network, ECN3

Main Organizer: Gilles Bruneaux (IFPEN), Raul Payri (CMT), Lyle Pickett (Sandia National Laboratory)

Summary

The 3rd workshop of the ECN was held 4-5 April 2014 in Ann Arbor, Michigan, USA, just before the SAE World Congress. Over 120 participants from 15 different countries representing more than 50 different institutions (more than 20 from industry) attended the workshop, and 40 more accessed the live presentations via webcast. The workshop addressed key stages of spray development and combustion, with 17 institutions contributing to experimental data and 19 different groups offering CFD simulations at these same operating conditions. Organizers gathered experimental and modeling results prior to the workshop to allow a side-by-side comparison and expert review of the current state of the art for diagnostics and engine modeling.

The presentations and discussions during the workshop were guided by the spirit of the ECN:

- A forum for open discussion and synthesis of modeling and experimental results, not usually found at conferences.
- Synthesis creates expert reviews on topics.
- We want to know what does NOT work, what is broken.
- Airing our dirty laundry, so that it can be cleaned!
- Policy is to not duplicate conference presentations.
- Not highlighting individual laboratories or groups, but rather, common research problems.

The objectives and the structure of ECN3 was based upon recommendations from past workshops and current research pathways. The organization for ECN3 sought to understand and connect what may seem as disparate phenomenon-for example, effects originating within the nozzle that affect combustion downstream. As a consequence, the ECN3 program was structured in 4 sessions addressing the four major topics listed below:

1. Internal flow, near-nozzle break-up, mixing, and evaporation. Focus on Spray A and Spray B, diesel conditions.
2. Mixing/chemistry interaction. Focus on Spray A and Spray B, diesel conditions.
3. Gasoline direct-injection spray research. Spray G.
4. Engine flows and combustion.

IMPORTANT NOTE ON USE OF THIS MATERIAL

Results of the ECN Workshop proceedings are contributed in the spirit of open scientific collaboration. Some results represent completed work, while others are from work in progress. Readers should keep this in mind when reviewing these materials. It is inappropriate to quote or reference specific results from these proceedings without first checking with the individual author(s) for permission and for the latest information on results and references.

Outcomes

A summary of findings, conclusions, and recommendations for future work are given in each of the following sections for various subtopics. However the main highlights are listed below:

- For the first time, coupled simulation of inside nozzle flow and near field spray have been achieved for Spray A and Spray B, and have been compared to experiments in a quantitative fashion. A new focus on understanding the relation between the internal nozzle hole geometry, internal flow field, and the near field liquid spray structure has emerged.
- While the first comparisons of advanced diagnostics realized by different institutions were presented at ECN2, ECN3 showed a generalization of these complementary advanced datasets:
  - Coupled advanced diagnostics of the near field spray structure (x-ray visualization at Argonne and optical microscopy at Sandia) and connection with highly detailed nozzle geometry (ESRF).
  - New information on chemistry-turbulence interaction: detailed information on the combustion structure by OH and formaldehyde LIF coherent between different labs (IFPEN, Sandia, TUe).
  - Extended soot database available, obtained with complementary Sandia/IFPEN datasets.
- Methodologies for the analysis of cycle-to-cycle variation in engine, and best practices for comparison between experiments and engine simulations.
- First Spray B and Spray G experiments and simulations.

Future directions

With this third edition of the ECN workshop, the ECN effort has now reached a “cruise speed” in methodology to address the important issues of the engine combustion communities through cross comparisons of experiments and simulation. Future directions towards ECN4 were discussed during the last session of the workshop. This discussion was based on a comparison between the directions discussed during ECN2 with the work effectively performed during the period. This comparison is available in the “future directions” presentation. Much progress has been made, but major items of future interest were discussed by the ECN participants:

- Spray C, cavitating large-nozzle-diameter (0.2 mm) nozzle: following the recommendation of ECN2 a set of 5 Spray C injectors were acquired from Bosch and are now available to the ECN community. In addition, a set of Spray D smoothed nozzles (KS1.5) with the same flow number as Spray C are available.
- Spray B, 3-hole version of Spray A: More realistic injectors than single-hole Spray A are of interest for engine applications. ECN3 has shown that Spray B produces transient spreading angles in a much different fashion compared to Spray A, further demonstrating the interest of this target.
- Wall impingement: it is also a path towards a more representative configuration. It will require a significant standardization effort to characterize the wall parameters.
- Supercritical issue: this is clearly a key subject that is being addressed within the ECN. Different investigation paths were discussed, including the possible analysis of sub- to super-critical transition when comparing different fuels and ambient conditions with specific thermodynamical characteristics.
- Multiple injections: preliminary experimental work showed that double injection strategies result in complex processes with a strong coupling between the injections.

- Fuel properties: this target is of interest for several reasons, ranging from the availability of chemical schemes to the investigation of super-critical issues. In the latter case the outcome of the discussion is that the use of single components is preferred to mixtures in order to avoid the related complexity concerning the knowledge of thermodynamic properties.
- Spray B or G in engine: a few groups showed interested in this direction. A coordination is needed to define the standardization method, i.e. the minimum requirements for engine characterization that will allow a pertinent comparison of the results between different engines and with CFD simulation.

TOPIC 1: Internal Flow, Near-Nozzle Mixing, and Evaporation

Session Organizer: Sibendu Som (Argonne National Laboratory)
Co-Organizers: Chris Powell (Argonne), David Schmidt (UMass-Amherst), Alan Kastengren, (Argonne), Qingluan Xue (Argonne), Julien Manin (Sandia), Chawki Habchi (IFPEN), Tommaso Lucchini (Poli.di Milano), Alessandro Montanaro (CNR Instituti Motori)

The present document summarizes the major outcomes and recommendations for future work regarding the ECN3 Topic 1.

MAJOR OUTCOMES

- Experimental work:
    - Rate of injection is extensively available for all the injectors of interest. Spray A showed faster rise of rate of injection during the initial transients compared to Spray B.
    - New results were shown for Spray B which is the multi-hole injector using x-ray radiography analysis to understand the differences between single and multi-hole nozzles.
    - Spray plumes from Spray B was observed to be wider, more dilute along the axis, and more dynamic compared to Spray A.
    - Injector aging was a major concern and best practices for handling the injectors were further reiterated.
    - Differences in spray characteristics for different Spray A injectors were mainly attributed to differences in nozzle diameters
- Modeling work:
    - In-nozzle flow simulations were performed using approaches with different model assumptions and geometries.
        - In general, the models could predict the experimental mass flow rate, Cd, Cv, and Ca reasonably well.
        - Significant differences between the models could be observed mainly owing to the differences in the treatment of boundary conditions, compressibility effects etc.
        - Simulations predicted more than 50K drop in temperature inside the injector. However, this cannot be confirmed from experiments yet.
        - Sub-merged nozzle simulations may not be appropriate since there is experimental evidence of ingested gas in the sac before every SOI event.
    - The x-ray radiography data in the near nozzle region was used for quantitative validation of coupled nozzle flow and spray models. Several variations of Eulerian models were presented and compared with a dense fluid model results.
        - In general, spray penetration is always over predicted and in most cases spray dispersion was also over predicted.
        - Overall, there is significant scope for improving these near nozzle flow models.
        - Eulerian approach seemed to perform better than the Lagrangian approach in the near nozzle region.

- Spray B was not simulated in detail. Preliminary simulations showed some plume to plume variations.
- The influence of many parametric variations such as ambient temperature and density etc., were qualitatively well captured by all the Lagrangian simulation approaches when compared against global spray data such as liquid length and vapor penetration. However, the local spray characteristics are significantly different between these modeling approaches.

RECOMMENDATIONS FOR FUTURE WORK

- Geometry for high-fidelity simulations necessitate high surface resolution of some key parameters such as orifice geometry, hydrogrinding, k-factor etc. STL files to be made available with high resolutions for these key features and lower resolutions for other geometrical features.
- Possibly measure droplet sizes for both Spray A and Spray B in the near nozzle region for more comprehensive validation of CFD modeling tools.
- Further quantify differences between single and multi-hole injectors and between different multi-hole injectors for different parametric variations.
- Possibly measure radial mixture fraction and velocity distributions in the near nozzle region i.e., upstream of 20 mm.
- In-nozzle simulations approaches should consider the effect of liquid compressibility, needle transients, temperature variations, and higher spatial resolutions.
- Consistent simulations approaches still need to be identified so that the influence of nozzle flow development on combustion and emission characteristics can be realized through one reliable simulation. Currently modeling approaches in-nozzle and near nozzle are quite different from combustion modeling approaches.
- Finally, two additional interesting topics were raised:
    - Possibility of performing conjugate heat transfer analysis between the injector and the flow-field.
    - Extension of experimental database to multiple injections or larger orifices.

TOPIC 2 : MIXING/CHEMISTRY INTERACTIONS

Session Organizer: José M García-Oliver (CMT)
Co-Organizers: Scott Skeen (Sandia), Michele Bolla (ETH-Zurich), Yuanjiang Pei (Argonne), Sibendu Som (Argonne)

The present document summarizes the major outcomes and recommendations for future work regarding the ECN3 Topic 2 work.

MAJOR OUTCOMES

- The ECN experimental database has been extended in different directions
    - New results from additional injectors for fundamental parameters (ignition delay and lift-off) have been produced, which seem to be quite in line with existing ones.
    - OH has been the focus of extensive investigation by means of OH-LIF. Analysis is still ongoing in three directions:
        - Comparison of measurements among different institutions (IFPEN vs TUe)
        - Comparison between OH* chemiluminiscence and OH LIF results.
        - Comparison between OH and 355 LIF to deliver information on combustion structure.
    - Soot database has extensively been characterized for Spray A and parametric variations by means of extinction imaging by Sandia. A comparison between this technique and IFPEN LII results has been performed, which indicated interesting similarities.
    - New quantitative indicators (flame length and reactive spray penetration) have been introduced, and the quantitative trends should be further analysed.
- On the other hand, modelling results showed the following conclusions:
    - Ignition delay is always overpredicted, while there is scattering regarding the lift-off.
    - Detailed analysis of flame evolution, mainly in terms of OH and CH2O show interesting similarities with experiments, in spite of differences in ignition delay, which has a large impact on flame development.
    - More analysis on the details is needed to try to elucidate if differences among modelling results are due to spray evaporation and mixing differences or to the turbulence-chemistry interactions models.
    - Soot models still need further work to enable the prediction of soot mass. In particular, the transient initial soot bump is not captured by the models, which is an interesting research topic.

FUTURE RECOMMENDATIONS FOR FUTURE WORK

- Chemistry mechanisms for Dodecane do not seem to perform well enough. This could be behind the above-commented overprediction of ignition delay. Therefore chemistry should be the focus of future work for ECN4.

    - Spray A with n-heptane was proposed as an additional way worth exploring, due to a better known chemistry, in spite of the limitations of most of the chemical mechanisms at high pressure conditions.
- A detailed analysis of flame structure in terms of OH/CH2O has been performed, but more validation is needed of other new quantitative indicators (flame length, reacting tip penetration), as well as other available results (PIV velocity fields). This should improve the description of the spray flow along time, which was originally a task for ECN3 which could not be achieved.
- It is highly recommended for the future that every group submitting reacting cases also submits an inert case, to enable a better description of the underlying mixing field.
- New experimental techniques are welcome, especially those delivering local variables under reacting conditions.
    - Following the previous point, radiation measurements may be interesting to enable a closer look into the soot effects.
- Finally, two additional interesting topics were raised:
    - After End of Injection flame dynamics.
    - Extension of experimental database to multiple injections or larger orifices.

TOPIC 3: SPRAY G GASOLINE DIRECT-INJECTION

Session Organizer: Scott E. Parrish (General Motors R&D)
Co-Organizers : Yongjin Jung (KAIST) , Peter Hutchins (Infineum/ESRF), Raúl Payri (CMT, Julien Manin (Sandia) , Gilles Bruneaux (IFPEN) , Luigi Allocca (IM), Josh Lacey (Melbourne), Ron Grover (GM), Noah Van Dam (UW), Tommasso Lucchini (Poli. Milano), Sibendu Som (ANL)

The ENC3 Spray G program was composed of summaries from four experimental activities including: nozzle geometry assessment, injection rate measurements, spray visualizations, and drop size measurements and two modeling activities including: internal nozzle flow simulations and external spray simulations. It was noted in the introduction of the session that the results and analysis of the material was preliminary due to timing of the workshop and that more rigorous analysis and data qualification would occur in the near future. The following provides a brief summary of each activity.

- Nozzle Geometry Assessment

Utilizing conventional optical microscopy at a resolution of 2.3 pixels/um, the inner and outer diameters of each nozzle hole of one injector were measured. In general it was found that the measured hole sizes were larger than the specified hole sizes. The inner and outer hole diameters were measured to be around 175 microns (165 microns specification) and 400 microns (388 microns specification), respectively. Preliminary examination of x-ray CT scans revealed that the inner holes are nearly cylindrical as specified. Further, more rigorous, analysis of the x-ray CT scans will be pursued in the future.

- Injection Rate Measurements

Injection rate measurements performed at two institutions for three injectors were compared. In all cases, measurements were quite similar at Spray G conditions. Resulting injected quantities ranged from 10.1 to 10.4 mg when operating with a fixed injection duration of 680 µs and 1 Hz injection frequency. Shot-to-shot deviation was found not to exceed 0.1 mg in all cases. Trends with fuel pressure, back pressure, and injection duration were as expected. Injectors were found to flow slightly more (0.1-0.4 mg) at 10 Hz injection frequency in comparison to 1 Hz injection frequency.

- Spray Visualizations

Liquid penetration measurements performed at four institutions with four different injectors were compared. Although there were significant differences in experimental methods and data processing, liquid penetration curves were found to be somewhat similar. The maximum liquid penetration at Spray G conditions was found to be around 30 mm. Liquid persistence was notable longer for one institution and was believed to be an artifact of image processing. Liquid spreading angle was measured by two institutions and was found to range between 70 to 80 degrees. Vapor penetration curves from three institutions for three injectors were compared and found quite similar, although in one case vapor penetration was significantly higher at later times and was believed to be an artifact of image processing. Vapor spreading angle was measured by two institutions and ranged between 80 to 100 degrees. Differences in image processing and angle measurement methodologies were cited as the primary reason for the variance. One institution performed penetration and spreading angle measurements on two injectors and results were nearly identical. High magnification near tip imaging was performed by one institution and the images revealed an asymmetry in the spray during closing along with emission of large droplets that appeared to propagate primarily in the axial direction.

- Drop Size Measurements

Time resolved phase Doppler interferometer (PDI) measurements at Spray G conditions were reported by one institution. Measurements were performed on a single plume, at an axial position of 15 mm from the tip of the injector. Results from a radial scan and a transverse scan through the center of a plume were shown. The average axial and radial droplet velocities were found to be approximately 50 and 35 m/s, respectively. Droplet sizes (SMD) ranged from about 10 to 12 microns. Comparisons of the PDI data with imaging data were performed and suggested that the PDI velocity magnitudes were reasonable.

- Internal Flow Simulations

Internal flow simulations were shown by one institution. Computations were performed utilizing HRMFoam with a fixed and fully lifted ball (needle). Incompressible and submerged fluid were assumed. The calculated steady-state discharge coefficient was determined to be 0.50 and compared well to the experimentally determined discharge coefficient of 0.52. The entire nozzle was modeled three-dimensionally and velocity cut planes at the inner and outer hole exits showed some variation from hole-to-hole. Discharge coefficients and resulting flow percentages were calculated for each hole and ranged from 0.47 to 0.60 and 11.4% to 14.5%, respectively. It was noted that these values correspond to an arbitrary point in time after the computed mass flow through the nozzle reached a steady state value and that a different point in time (or time averaging) may result in different results.

- External Spray Simulations

External spray modeling results were shown by three institutions. Different codes (CONVERGE, OpenFoam, and Kiva-3V) were used by each institution. Model details including assumptions, sub-models and grid sizes were provided in each case. Liquid and vapor images and resulting axial penetration curves were compared with experiments and agreement was reasonable. Mixture fractions and droplet sizes (SMD) were compared along three different lines all located in a plane normal to the injector axis, 15 mm below the injector tip. The locations of the lines included: a radial line through the center of a plume, a transverse line through the center of a plume, and a line passing through the centers of two adjacent plumes. Trends in mixture fraction were similar although magnitudes varied significantly (more than a factor of 2) particularly early in time. Drop size comparisons varied widely with magnitude variations in excess of a factor of 4. It was noted that some results were indicative of the simulations being under-resolved and that better agreement may have been achieved if equivalent resolutions were employed.

TOPIC 4: ENGINE FLOWS AND COMBUSTION

Session Organizer: David Reuss (University of Michigan)
Co-Organizers: Brian Peterson (TU Darmstadt) and Cecile Pera (IFPEn)

Main Outcomes

- Four different optical SI engines and experimental SI data bases were identified for LES Bench marking. The attributes of each engine and available data each were exhibited.
  - UM/GM/PSU/UW consortium, TCC engine, 2 valve, pancake, homogeneous, SI, engine
  - TU Darmstadt 4 valve, pent roof, SI, wall-guided direct-injection engine.
  - IFP , SGEmac 4 valve pent, roof, homogeneous, SI
  - Sandia/U Duisburg-Essen 4 valve, pent roof, homogeneous-hydrogen, SI, engine.

=> Maarten Meijer TU/Eindoven agreed to coordinate a group of 3 nominally identical Diesel engines available in Europe.

=> Dave Reus agrees to post new data for transition from TCCII data to the TCCIII data sets.

- Three topics for Simulation-to-Simulation Benchmarking were proposed, including meshing Strategy, Boundary Condition methodology, Numerics, RANS vs. LES, Gridding, and modeling.

=> Satbir Sing agreed to coordinate research groups interested in assessing (1) the impact of different SGS models on resolved scales, (2) interfacing of numerical errors with SGS models and (3) filtering for reducing numerical errors.

=> Cecile Pera proposes to coordinate research groups interested in meshing strategies using the TCC and/or TU Darmstadt engine.

- Topics “Benchmarking Simulations with Measurements” and “Exploring CCV origin” resulted in no specific interest form the modeling or measurement communities.

=> Dave Reuss will work with and simulation efforts using the TCCIII to identify collaboration opportunities on these topics.