ECN Workshop 2 – Spray development and vaporization

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Summary of the Spray Development and Vaporization session

- Four institutions have provided liquid length and penetration data according to the standard measurement techniques proposed after ECN 1.
- Diffused back-illumination has been used as the reference diagnostic to measure liquid penetration as a function of time with the main goal being to quantify and compare liquid length between institutions.
- Schlieren still is the reference diagnostic to measure spray vapor penetration.
- 2-D and 3-D modeling has been performed with the injection rates corresponding to the different injectors to evaluate the expected differences in terms of liquid and vapor penetration at Spray A condition.
- The differences measured in spray penetration can be explained by the nozzle diameter differences, but sometimes, no difference is observed when expected.
- Extinction profiles measured with DBI shows similar peak extinction but for CMT's measurements, which measured significantly higher peak extinction, while resulting in shorter liquid penetration (than Sandia using the same injector).
- Experimental Liquid penetration as a function of time is relatively close for all laboratories, showing similar fluctuations; IFPEN's standard deviation exhibits high peaks while TU/e's is lower (mean value is similar though) when they both have similar values for liquid length vs. time and time-averaged.
- Higher collection angle of the long-distance microscopic experiments show that beam steering was not as severe and extinction would go down to zero rapidly after the liquid length region.

- Six groups provided simulation results using both commercial (CONVERGE, FLUENT) and open-source (OpenFOAM, KIVA) codes. The liquid penetration definition used was mostly consistent between different groups. The vapor penetration definition was always consistent between different groups.
- Many groups performed simulations according to the suggested baseline conditions. The main deviations from baseline conditions were in the minimum grid-size and dimensionality of the simulation (2-D instead of 3-D).
- Most groups performed simulations using a Lagrangian approach for liquid spray computations, whereas, CMT used an Eulerian approach.

- GA-Tech and UNSW simulated a smaller nozzle diameter of approximately 84 µm in order to match the first dataset published by Sandia (using injector 210677), while the other labs used 89 or 90 µm as recommended in the guidelines.
- Parametric variations on effect of ambient temperature, ambient gas density, and fuel injection pressure were used to test the performance of the models
- Liquid spray penetration vs. time, vapor penetration vs. time, Liquid length vs. ambient temperature, vapor boundary location were used for validation of the models
- Comparison of peak cell count, wall-clock times, number of cores used for simulations was also shown
- Additionally, x-ray radiography data was used for validation purposes in the near-nozzle region. ANL and CMT used this data for validation of their simulation approaches.

Conclusions

- Experimental results have been provided by 4 different institutions carefully following the recommendations from ECN 1
- Experiments are a continuous challenge even if the original idea is to make the setup "the same", slight variations have a hardly quantifiable impact on the results
- Nevertheless, the contribution from the different facilities is globally satisfactory as variations in hardware (injector for instance) have been identified
- Using simple techniques is needed in order to assess overall measurements validity when more complex/unique diagnostics are applied
- There is a strong need for high fidelity measurements and application of advanced diagnostics from the modeling community in order to understand the physics of internal nozzle flow, liquid jet atomization and global spray development better

- Overall conclusion from the modeling session is that the simulations can capture the experimental trends quite well under different ambient conditions, however, the quantitative values are different from experiments
- With Eulerian-Lagrangian models, improving grid-resolution does not necessarily result in better results. Grid-refinement also necessitates increasing the number of parcels injected
- ANL simulations can capture the global spray characteristics well. Vapor penetration is generally under-estimated after 0.6ms
- CMT approach with the Eulerian model overall provides the best predictions for parameters investigated in this session. However the approach is 2D in nature and may need to be extended to 3D?
- ERC OpenFOAM approach can capture global spray characteristics using a coarse (1mm) mesh. Near-nozzle vapor penetration needs to be better assessed
- GA-Tech simulations can capture the global spray characteristics well. Need to inject more parcels and improve the resolution
- Polimi simulations can capture the global spray characteristics. Near nozzle spray penetration at lower injection pressures need to be improved
- UNSW does an excellent job in capturing vapor penetration profiles. Need to improve liquid spray penetration

Discussions/Questions

- What caused these differences in standard deviation for the liquid length as a function of time between IFPEN and TUe?
  It appears that errors coming from the initial processing affected the global standard deviation for liquid-length as a function of time from IFPEN, TUe's standard deviation was right (correcting the initial thought), as confirmed by the new processing for IFPEN's data showing very similar results to TUe's.
- What caused the differences in light extinction along the spray axis in DBI?
  The parameters affecting liquid length are well-known and have been analyzed during the workshop, nevertheless, the optical arrangement set up to perform DBI experiments also has an impact on the measured liquid length. The distances, lenses used, as well as the dimensions of the high-pressure, high-temperature chamber will all affect the results to some degrees.
- What is the effect of grid-size on simulation results?
  Grid-size has a strong influence on both liquid and vapor penetration results. The influence of grid-size on results for different codes was not accessed as part of this ECN study. However, several different groups have papers demonstrating this work in the past.
- How are differences due to injection pressure effects accounted for in terms of Cd, Cv, and Ca?
  Depending on the complexity of the nozzle flow model being used, these details can be provided. Most models need the Cd information only. A constant Cd value is usually used in the simulation which corresponds to a quasi-steady needle lift position.
- At lower ambient temperatures the calculated spray penetration definition from simulations needs to be re-evaluated since different definitions may lead to different answers.
- To determine the vapor boundary/profile, is the definition consistent with the vapor penetration definition?
  Yes
- It was noted that different models with various constants were able to predict the spray characteristics quite well. This is due to the fact that the sprays are mixing controlled.
- Is it better to use one nozzle only for spray characterization rather than using multiple nozzles?
  Using different nozzles with geometric variations is useful for the groups performing inner nozzle flow simulations since full nozzle details are critical for nozzle flow simulations. As far as the spray simulations are concerned, if the appropriate boundary and geometry information is available, the full nozzle details may not be critical.

Experimental uncertainties

- All the results reported are coming from several experiments and averaged, the uncertainty of these averaged results is therefore getting lower as the number of repetition increases; for all the measurements and comparison between institutions, 10 repetitions have been used to generate the results.
- Concerning the hardware only, the differences in spray penetration is expected to be on the order of 8 to 10 % because of the different mass flow rate (different orifice diameter) of the injector used, similar observations have been made concerning liquid penetration.
- Although DBI was chosen to reduce the uncertainty and variability in the experiments when comparing the results from different labs, the results presented here show that some variability still exists. While it has been significantly reduced after ECN 1 and the use of the diffused back-illumination technique, differences higher than 10 % can still remain.
- Schlieren technique seems not to suffer from such discrepancies as the results are more consistent with hardware among the different institutes.

Recommendations and bottom line

- Different experimental facilities/optical arrangements provide different results. The reasons for these variations are still under investigation at that time.
- As a general recommendation concerning liquid length measurements using the diffused back-illumination is that the optical setup must be followed carefully. It has been observed that distances and lenses (illumination and collection angles) have larger effects than expected and they need to be respected or no comparison is valid.
- The schlieren experiments followed the guidelines and recommendations prescribed after ECN 1 and we feel that the schlieren experiments were successfully describing the spray development, considering the limitations of the technique.
- Simulations can capture the experimental trends quite well under different ambient conditions; however, the quantitative values are different from experiments. The reason for these different numerical results need to be investigated.
- Models need to focus on comparing the spray structure against experimental data (profiles of mass fraction, liquid and vapor volume fractions)
- Development of new models that link in-nozzle flow simulations together with the near-nozzle spray models, is necessary.
- More experiments are available now and future computations will be able to be compared against new data-sets available on the ECN website.
- There is a strong need for high fidelity measurements (for instance, standard deviation of gas and liquid temperature smaller than 10K, errors on in-nozzle geometry information on the order of 1 micron, …) and application of advanced diagnostics in order to understand the physics of the injection and spray development processes.