2nd International Workshop of the Engine Combustion Network, ECN2

Summary

The 2nd workshop of the ECN was held 7-8 Sept. 2012 in Heidelberg, Germany directly after the ICLASS meeting. Over 100 participants from 20 different countries attended the workshop, and 40 more accessed the live presentations via webcast. The workshop addressed key stages of spray development and combustion, with 8 institutions contributing experimental data and 16 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. Sharing results in this open exchange facilitates rapid evaluation of the state of experimental and modeling activities and points to needed future directions.

The experimental and modeling activity at focused target conditions for Spray A has been massive. Over 25 different types of experiments have been performed to date, with many of the same experiments repeated at different institutions to verify consistency. Collectively, this effort is bringing forth an important dataset that is the focus of model validation. ECN2 was organized with three major objectives that were followed in many activities and web meetings well before the actual workshop:

- Evaluation of modeling and experimental results at parametric conditions beyond Spray A for a more rigorous evaluation of CFD modeling. For example, ambient temperature, oxygen concentration, and injection pressure were varied while holding all other conditions constant.
- Direct comparison of modeling and experiment based on the topic, rather than conditions, with emphasis on the need to standardize and quantify experimental and modeling activities. Focus topics include: internal nozzle flow, spray development and vaporization, mixing and turbulence, ignition and lift-off length, soot formation, and so forth. Teams of coordinators were organized around such topics, collecting and analyzing all experimental and modeling input data. Best practices for further standardization with variation in conditions were offered.
- Planning activities for gasoline sprays and engine flows activities, including the selection of common hardware and operating conditions. Delphi has agreed to donate 12 gasoline injectors for future ECN research.

A summary of findings, conclusions, and recommendations for future work are given in each of the following sections for various subtopics.

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

The systematic coordination and standardization between experimental and modeling efforts yielded new understanding about differences between injectors and facilities, including uncertainties with respect to boundary conditions and how these uncertainties impact experimental results. This standardization had not been accomplished at ECN1, particularly with respect to the modeling work. Modelers now used the same definitions for standard quantities such as liquid and vapor penetration to allow an apples-to-apples comparison. A few notable outcomes are included below, while more detailed explanations appear with each subtopic:

- Quantification of nozzle geometry and needle movement shows differences between injectors that can be related to the near-nozzle liquid distribution and spray penetration.
- Mixing (Sandia) and velocity (IFPEn) measurements have been acquired downstream of the liquid-phase penetration region for the first time, representing a unique dataset for diesel-condition sprays. These measurements show self-similar behavior consistent with expectations for a gas jet. CFD models that match the velocity data also appear to match the mixture fraction data, or vice versa, indicating consistency between datasets obtained at different institutions.
- Although there are known differences in liquid penetration and spray shape because of nozzle or facility differences, the combustion (ignition delay and lift-off length) measurements show consistency between institutions, suggesting a certain insensitivity of the spray details to the ultimate combustion, at least at Spray A conditions. It should be noted, however, that ignition and lift-off length (16-17 mm) occur downstream of the liquid length (10-11 mm), which certainly may affect this conclusion.
- CFD modeling attempts to capture trends with respect to ignition delay and lift-off length show relative errors are higher for ignition delay, and higher for n-dodecane compared to n-heptane. The modeling relative errors for variation in temperature are much higher than the experimental variance between facilities, indicating that progress is still needed and should be expected.

Future directions

While the modeling and experimental comparisons have been quite extensive, and expanded significantly since ECN1, ECN participants recognize that the research ideas are still developing and have only focused on two primary targets: Spray A and Spray H. There are obviously many different directions that could be pursued in the future with the constraint of voluntary participation within the ECN. Rather than choosing yet another spray or engine target, organizers suggested that it would be best to focus on common physical problems that are of most interest experimentally and computationally, and to use these problems to define future research plans. Three physical problems that were identified include:

- The need to understand internal nozzle flow and geometry and its connection to the near-field spray development.
- The possibility that sprays become “supercritical”, acting as a dense fluid, rather than a two-phase system with surface tension.
- Flow/chemistry interactions at realistic “engine-type” conditions, including liquid/flame interactions, transient head penetration, multiple injections, and wall impingement.

In response to the outcomes and physical problem identification, several directions for future research were outlined:

- Large-nozzle injectors of approximately 0.2 mm diameter should be used to test cavitation effects with internal nozzle modeling, and to create an interaction between liquid regions and combustion regions of the spray.
- Operating conditions and experiments for gasoline injectors shall be determined and advertized as initial experimentation gets underway.
- Focus on target conditions such as Spray A has been successful and should continue. Comparisons should go deeper to understand the cause for differences in the near-nozzle region, as well as combustion interactions downstream.
- Transients of jet head penetration and multiple injections should be pursued.
- Quantification of lift-off length, ignition location, and any scalar should be pursued using planar or point measurements to enable more strict evaluation of model against experiment and of different CFD simulations.

ECN2

2nd Workshop on Spray Combustion

Heidelberg, Germany ■ 7-8 September 2012

Program

Friday 7 September

8.00 Registration

9.00 Introduction and mechanics
Gilles Bruneaux (IFPEN), Lyle Pickett (Sandia)

9.20 Engine flows
Sebastian Kaiser (U. Duisburg-Essen)

9.50 Discussion

Diesel Spray Target Conditions

10.00 Internal flow and geometry
Chris Powell (Argonne), David Schmidt (UMASS Amherst), Marco Arienti (Sandia)

11.20 Discussion

11.50 Lunch

13.00 Spray development and vaporization
Julien Manin (Sandia), Sibendu Som (Argonne), Chawki Habchi (IFPEN)

14.20 Discussion

14.50 Break

15.30 Mixing and velocity
Louis-Marie Malbec (IFPEN), Gianluca D'Errico (Politecnico di Milano)

16.50 Discussion

17.20 Gasoline spray combustion
Scott Parrish (GM)

17.50 Discussion

18.00 End of the 1st day technical sessions

19.00 Workshop dinner in ***Kulturbrauerei Heidelberg*** *(Leyergasse 6)*

Saturday 8 September

9.00 Ignition and lift-off length
Michele Bardi (CMT), Evatt Hawkes (UNSW), Christian Angelberger (IFPEN)

10.20 Discussion

10.50 Break

11.10 Soot
Emre Cenker (U. Duisburg-Essen, IFPEN), Dan Haworth (Penn State)

12.00 Lunch

13.00 Soot (continued)

13.30 Discussion

14.00 Future directions

15.00 Birdie / vortex interaction in strongly accelerating flows...

Workshop overall program organizers:
Gilles Bruneaux (IFP Energies nouvelles), Lyle Pickett (Sandia)

Internal Injector Flow Session

Group Leaders: Marco Arienti (SNL), Chris Powell (ANL), David Schmidt (UMass)

Contributors: Alan Kastengren (ANL), Thomas Furlong and Caroline Genzale (GA Tech), Sukanta Rakshit (UMass)

Progress Summary:

X-Ray tomography measurements by Argonne and Caterpillar have produced updated assessments of the nozzle geometry that reveal a more irregular nozzle exit for Spray A than previously indicated by silicone molding. Argonne's X-ray phase-contrast measurements have also documented the transient needle motion for Spray A injection. Argonne's X-ray measurements were used to assess the spray-H geometry as well.

All existing geometry characterizations produce nozzle surfaces with some degree of noise while also reflecting the irregular as-built shapes of the nozzles. Georgia Tech has developed an algorithm to smooth small irregularities in the measured nozzle shape while preserving larger scale shape information. This filtered geometry can then be used as the basis for generating computational meshes.

Modeling was performed using a simplified geometry based on the silicon mold shape. Modeling was performed using two compressible models and static geometry (UMass and Georgia Tech). Simulation results by Sandia with moving boundaries is forthcoming.

Findings:

- The transition from experimentally-measured geometry to computational geometry is a significant barrier to producing simulation results.
- Modeling results show no indication of cavitation in Spray-A. The absence of cavitation is due to two factors: the large degree of conicity of the nozzle shape and the assumed smooth walls. Modeling groups have expressed interest in Spray A, even if non-cavitating.
- Compressibility effects and nozzle convergence in Spray-A cause significant density drop and acceleration of the liquid as it transits the nozzle.
- Spray-H was found to cavitate, but the predicted nozzle discharge was very sensitive to the assumed inlet corner radius.
- The existing uncertainty in the measured inlet nozzle corner is a dominant error in the prediction of sharp nozzle discharge, such as in Spray-H

Recommendations and Future Directions:

- Spray-H is obsolete and its geometry is inadequately characterized. The workshop participants indicated that a 2X larger, transparent nozzle would provide a future target to replace Spray-H.
- Future modeling will test the efficacy of the proposed computational geometry process being developed at Georgia Tech.

- Experimentalists are hoping to find time to study Spray B, but continued interest in Spray A is the priority for most. It is suggested that a sharp-edged versions Spray A nozzles be obtained to study cavitation.

ECN Workshop 2 – Spray development and vaporization

Session organizers: Julien Manin (Sandia National Laboratories), Chawki Habchi (IFPEN), Sibendu Som (Argonne National Laboratory)

Contributors (Experiments): Julien Manin and Lyle Pickett (Sandia National Laboratories), Michele Bardi and Raul Payri (CMT – Motores Termicos), Maarten Meijer (Technical University Eindhoven), Louis-Marie Malbec (IFPEN) and Alan Kastengren (Argonne National Laboratory)

Contributors (Modeling): Sibendu Som, Kaushik Saha, Douglas E. Longman (Argonne National Laboratory); Jose M. Pastor, A. Pandal, R. Novella, J.F. Winklinger (CMT-Motores Termicos); Gina Magnotti, Caroline Genzale (Georgia Tech.); Chi-Wei Tsang, Chris Rutland (University of Wisconsin at Madison); Gianluca D'errico, Tommaso Lucchini, Roberto Torelli (Politecnico di Milano); Yuanjian Pei, Evatt Hawkes (University of New South Wales)

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.

Mixing and Velocity session

(A summary by the session coordinators:
Louis-Marie Malbec, IFP Energies nouvelles, France, email: louis-marie.malbec@ifpen.fr;
Gianluca D'Errico, Politecnico di Milano, Italy, email: gianluca.derrico@polimi.it)

Experimental Results

This part of the session focused on the experimental results:

- mixture fraction measurements performed by Sandia, through Rayleigh scattering technique (see SAE 2011-01-0686)
- velocity fields measurements (inside and surround the spray) performed by IFPEN using high speed PIV.

Mono-parametric variations of the boundary conditions have been performed:

- injection pressure variations: 150, 100 and 50MPa (only for mixture fraction for these latter condition)
- ambient temperature variations: 900 and 1100K
- ambient density variations: 22.8 and 15.2kg/m3

Rather than on the results in themselves, the presentation was focused on 2 points:

- how to assess the accuracy of the boundary conditions?
- how to compare PIV and Rayleigh scattering results, because they were obtained in 2 different facilities?

The main outputs of this presentation are:

- With high speed PIV, it is possible to obtain on a single injection event both the velocity fields inside and surrounding the spray.
- Both the PIV and Rayleigh scattering results show radial profiles that are Gaussian profile.
- Once the spray penetration is known, a 1D model based on the momentum conservation (proposed by Siebers, Musculus and Pickett) adequately predicts the mixing and velocity distributions of the spray, including the radial profiles. Therefore, this model can be used for assessing the accuracy of the boundary conditions, and to assess the consistency of the data obtained in 2 different facilities and for 2 different physical values (mixture fraction and velocity fields).
- Based on the results from this 1D model, it seems that the mixture fraction data obtained at Sandia, and the velocity data obtained at IFPEN, can be used as a single dataset for modelers, describing the mixing processes occurring in the spray.

Recommendations/future work:

- Difficulties have been encountered to measure the velocity fields near the nozzle tip (no data are available under 30mm). The reason for this must be analyzed, and some solution proposed.
- Data concerning the air entrainment need to be analyzed.

Modeling contributions

This part of the session compared models and experiments of mixture fraction distributions and velocity fields for the non-reacting Spray-A spray.

The following seven groups contributed modeled results:

- Argonne National Laboratory: S. Som, D.E. Longman
- Chalmers University of Technology: A. Kösters, A. Karlsson
- Universitat Politècnica de València CMT: R.Novella, A. Pandal, J.M.Pastor, J.F. Winklinger
- Georgia Institute of Technology: C. L. Genzale, G. Magnotti

- Politecnico di Milano: G. D'Errico, T. Lucchini, R. Torelli
- University of Wisconsin, Engine Research Center: C. Rutland, C-W. Tsang
- The University of New South Wales: E. Hawkes, Y. Pei, S. Kook

Most groups of this session, contributed to the previous Spray and Development session.
All groups used RANS turbulence models. Most of the spray models were based on the Lagrangian discrete phase approach, though one group (CMT) contributed an Eulerian approach.
Despite the fact that some standard/baselines guidelines were given, all groups preferred to use their choice of spray sub-models and only few groups submitted results with the suggested set-up guidelines. However, at the end of the discussion, conclusions sounded to be independent on the spray sub-model choice.

Comparisons between measured and computed data were performed at centerline and at two radial positions (25 mm, 45 mm). Effects of fuel injection pressure, ambient density and temperature were evaluated.

Modeling results and comparison with measured data

The comparisons at the baseline condition were good for the majority of the models, confirming also the consistency between the mixture fraction and PIV velocities data, as mentioned in the comments of the experimental part of the session. Some discrepancies between measured and computed velocity results appeared at the 25 mm sample, but at this location the PIV data had a very high standard deviation.

Modeling results differed in the near nozzle region, where no measured data was available. Both mixture fraction and velocity profiles suggest different interpretations of the occurring physical phenomena by the available modeling contributions.

Two groups (PoliMI, UNSW) provided mixture fraction variance results too and in both cases measured and computed values were in good qualitative and quantitative agreement.

With respect with the variations of the operating conditions the following conclusions were drawn:

- models were able to reproduce the effect of variations of the fuel injection pressure;
- models were sensible to ambient density. Results differed a little, but it was not possible to make a definite quantitative assessment on the basis of the available experimental data;
- no experimental data was available for the temperature variations at constant density. All models predicted similar variations of the mixture fraction and the velocity with the ambient temperature;

Finally a series of comparison between results provided by some of the groups with different CFD and similar model set-up were shown. Obtained results were similar but not identical and comments on the comparison were analogous to the ones which were done in the previous analysis.

General conclusions and future suggestions.

The comparison between measured and computed velocity fields and mixture fractions evidenced some good predicting capabilities of the tested modeling approach under the chosen operating conditions. Some differences among modeling results were evidenced in the near nozzle region and should be matter of future investigation.

All analyses were performed at steady state conditions. The modeling and experimental analysis under transient conditions should be matter of future investigation. Besides, the use of longer injections would be preferable to verify that the behavior of the spray is fully steady-state.

In all the conditions the spray evolution was observed to be mainly momentum driven, which also explains the similarity among the different models and contributions. Because the liquid penetration is quite short for Spray A (~10mm), the necessity to consider in the future injector holes with a larger diameter was suggested in discussion. Larger diameter nozzles would present liquid and vapor together downstream as the maximum liquid penetration scales with nozzle size.

Engine Combustion Network: 2nd Workshop on Spray Combustion

Ignition and lift-off session

Contents: Page 1: Experimental work (Michele Bardi)
Page 2: Comparisons of models and experiments (Evatt Hawkes)

Experimental work

A summary of the experimental sub-session by coordinator Michele Bardi, CMT, mbardi@mot.upv.es
22/11/2012

LOL and ignition delay have been measured by the participating institutions at spray A conditions and for parametric variations about spray A.

Experimental setup

Time-averaged lift-off length: IFPEN, CMT, SNL agreed on the methodology using a narrow band-pass filter (310±5 nm) and an intensified camera. A long gate time was employed to obtain a time-averaged image (2 to 5ms ASOI for CMT and SNL, 0.8 to 1.3 for IFPEN). TU/e used a CMOS fast camera coupled with an intensifier (LaVision IRO) and a (310±5 nm) band-pass filter. The time-averaged image was obtained by the ensemble average of the images falling in the interval from 1.5 to 2 ms ASOI.

Ignition delay/time resolved LOL: CMT and SNL used broad band chemiluminescence imaging (CMOS camera, low pass filter <600 nm, with regular lens, 50 µs shutter time). IFPEN used the same setup with no filter. TU/e obtained ID and time-resolved LOL from the same experiment described the previous paragraph. Moreover TU/e tried an unfiltered test to improve the sensitivity to cool flames.

Results

LOL measurement: The time-averaged images were analyzed with the same processing method and a good consistency emerged between the facilities at spray A baseline conditions, (LOLsnl =17.2mm, LOLCMT =17.7mm, LOLTU/e =16.5mm, and IFPEN = 16.9mm). From the wide test matrix performed at CMT an empirical relationship has been developed to correct the bias that the real boundary conditions have from the boundary conditions. Moreover, the dependence on the outlet diameter from SAE 2005-01-3843 has been used to scale all the data to nozzle #677, the nozzle used by modelers. However the spread of the data remains similar: LOLsnl =17.46mm, LOLCMT =17.40mm, LOLTU/e =16.5mm, and IFPEN = 16.61mm.
The analysis of the time resolved LOL data showed that there are significant fluctuations of the LOL along the injection: the camera synchronization chosen has an impact on the results and likely explains the differences in the results observed.

The parametric variations tried showed good consistency between the different facilities. A higher increase in LOL in is observed for CMT and CAT (ECN1 data) when ambient temperature is reduced, but this difference is significant only below 800 K. This may be related to the presence of minor species in CVP or to some issue related to temperature boundary layer.

The selection of the threshold used for the LOL definition has a strong impact on the results and needs to be discussed when the LOL is computed at different test conditions. The suggestion is to scale the threshold for each test condition to the half of the intensity peak that is visible right after the LOL.

The comparison of the data obtained via broadband chemiluminescence data showed good consistency with OH* chemiluminescence data. However much care should be taken in avoiding background/liquid fuel reflection and saturation: all these factors contribute to modifying the intensity levels in the lift-off length region and thus reducing the accuracy of the measurements.

Cool-flames have not been detected by all the institutions due to different sensitivity of the camera and the different f/# of the lenses employed. The use of an intensifier (TU/e) without filter did not provide significant improvements for the detection of cool-flames. However, combining the intensifier with the 310 band-pass filter allows precise detection of the second stage ignition. Even if the reference level of the cool flames could not be detected in all the cases, the sharpness of the intensity rise at the second stage ignition made the ignition delay measurement quite insensitive to the threshold adopted.

The values calculated by all the institutions are pretty close to 400 μs ASOI (IDsnl =400 μs, IDCMT =441 μs, IDTU/e =400 μs and IFPEN = 405 μs). The response to ambient temperature is pretty close for all the institution. Similarly to the LOL measurements, below 750K the ignition delay increases more for CMT rather than SNL, suggesting a consistent difference in the boundary conditions (temperature boundary layer / gas composition).

The comparison of pressure measurements from the CVP vessels showed consistency of the measurements with the data from chemiluminescence. The signal/noise ratio during the combustion is the most important issue of this technique: SNL showed that using an optimized setup it is possible to have a clear insight of cool flames and to distinguish them from second stage ignition under different test conditions (from 750 to 1200 K).

Comparisons of models and experiments

A summary of the modelling sub-session by coordinator Evatt R. Hawkes, The University of New South Wales, Sydney, Australia: evatt.hawkes@unsw.edu.au
17/11/2012

Scope

The session was focused on comparisons of models and experiments relating to lift-off length, ignition delay, and other available measures relating to gas-phase chemical reactions. Both n-heptane (spray H) and n-dodecane (spray A) were considered.

Objectives

The objectives were to compare different models against experiments for the purposes of validation and to identify what works and what needs improving, specifically in relation to issues of chemistry and turbulence-chemistry interactions.

Contributions

The following eight groups contributed modelling results:

- Argonne National Laboratory (ANL) – Sibendu Som, Douglas Longman
- ETH Zurich (ETH) – Michele Bolla, Yuri Wright, K. Boulouchos, G. Borghesi, E. Mastorakos
- IFP-Energies Nouvelles (IFPEN) – Julien Tillou, Christian Angelberger
- Pennsylvania State University (Penn. State) – S. Bhattacharjee, J. Jaishree, H. Zhang and Dan Haworth
- Politecnico di Milano (PoliMI) – Gianluca D’Errico, Tommaso Lucchini, Roberto Torelli
- Purdue University (Purdue) – John Abraham, Muhsin M. Ameen
- TU Eindhoven (TUe) - Sridhar Ayyapureddi,Ulaş Egüz,C. Bekdemir, L. M. T. Somers, L. P. H. de Goey
- University of New South Wales (UNSW) – Yuanjiang Pei, Evatt Hawkes, Sanghoon Kook

The contributions encompassed a range of different modelling approaches. Most of the contributions were RANS-based, and employed Lagrangian discrete phase models of the spray. An exception on both counts was IFPEN who contributed an LES model with an Eulerian approach to the spray. Several different approaches were used for modelling turbulence-chemistry interactions. A number of groups contributed well-mixed models, which ignore turbulent fluctuations of the thermochemical state. Compared with ECN1 there were more contributions using more sophisticated approaches. IFPEN, Purdue, and Tue contributed flamelet models, ETH contributed a Conditional Moment Closure (CMC) model, while UNSW and Penn. State contributed Transported Probability Density Function (TPDF) models.

The session was coordinated by Evatt Hawkes (UNSW), Michele Bardi (CMT), Christian Angelberger (IFPEN) and Yuanjiang Pei (UNSW).

Experimental/modelling comparison methods

A recommendation of ECN1 was to try to standardise and improve the methods for comparing experiments and models. Progress was made in this direction in ECN2, but differing definitions between modelling groups and between models and experiments still persisted.

Ignition delay

Experimentally, ignition delay was measured from the timing of sharp rises in chemiluminescence or pressure, which as discussed in the experimental part of the session, give consistent results. For the modelling, two definitions were recommended after ECN1:

1. First time at which Favre-average OH mass fraction reaches 2% of the maximum in the domain after a stable flame is established.
2. Time of maximum rate of rise of maximum temperature.

The definitions were compared using UNSW model results with two different models and agreed well. Five of the eight groups had used the recommended definitions in their contributed results.

Lift-off length

In the experimental session, it was recommended that lift-off should be measured using OH* chemiluminescence by finding the point of 50% rise of the chemluminescence to its peak value at the leading edge of the flame. After ECN1, it was recommended that the model definition should be given as the first location where ground state OH reaches 2% of its maximum in the domain. This definition proved controversial in ECN2 with many groups preferring locations which were further downstream.

UNSW implemented an OH* sub-mechanism in their model, and used a line-of sight integration of the OH* concentration in an attempt to obtain a surrogate for a chemiluminescence signal. Although the OH* sub-mechanism contains some known limitations, the results showed that OH* could have a very different profile to OH. The excited state showed a clear peak in the upstream region while the ground state levels increased monotonically downstream, owing to the presence of OH in the product gases. Thus it is not clear the extent to which OH can be used to determine lift-off in the models, and what OH threshold should be applied.

Analysis of UNSW's results for Spray A indicated that the lift-off predictions were significantly different between the different definitions adopted by the different groups, ranging from 17.5mm to 21.8mm. These differences were frequently as large as the differences between models and between models and experiment.

Model standardisation and boundary conditions

Chemistry models: For n-dodecane, it was recommended that the mechanism reported in [1] be adopted. For n-heptane, mechanisms reported at [2] and [3] were suggested. Amongst the contributions, there was a good convergence of chemical models for n-dodecane. For n-heptane the convergence was improved relative to ECN1 but there were still differences between the choices made by different groups.

Turbulence-chemistry interaction models: It was suggested that several groups could implement a well-mixed combustion model for comparison with the other models. Several groups did this, which resulted in some useful findings that will be discussed shortly.

Other: Standardisation of other elements such as spray models, numerical parameters such as grid, etc, was not attempted.

Comparison of experimental and modelling results

Conditions considered

- For Spray A, we considered a baseline ambient condition of 15% O_2, temperature 900 K, density 22.8 kg/m^3, with a 150 MPa injection pressure and 4 ms injection duration. We considered variations of temperature from 750 K to 1200 K and variations of oxygen from 13 to 21%.
- For Spray H, we considered a baseline of 21% O2, 1000 K, 14.8 kg/m^3, with 150 MPa injection pressure and long injection duration >4ms.

Overall remarks
Overall there was good agreement for qualitative trends for both ignition delay and lift-off length with some outliers. Most models over-predicted ignition delay and lift-off length for spray A while results straddled the experiments for spray H. The absolute agreement in both cases deteriorated with decreasing temperature and oxygen concentration. However, for ignition delay, relative errors remaining roughly constant across the temperature range considered.

Based on the contributions which were received, three questions were posed:
1. Do we get the same results with well-mixed models in different codes, etc?
2. Do flamelet and CMC methods give superior results compared with well-mixed models?
3. Do transported PDF methods give superior results compared with well-mixed models?

Do we get the same results with well-mixed models in different codes, etc?

For spray A, three groups had contributed well-mixed models and the chemistry models were also quite similar. Analysis of the results however indicated that despite the nominal similarities of the methods, we still obtained different results, which were the same order of magnitude as the differences between the different models and experiments. This indicates there is still a non-negligible influence of numerical errors or other peculiarities of the implementations.

Do flamelet and CMC methods give superior results compared with well-mixed models?

Several contributed results with flamelet-based methods were very good. However, the overall performance across the different groups and experiments considered was mixed. Comparison of the flamelet approaches with simpler well-mixed models was difficult because side-by-side runs were not done keep other factors held fixed.

The CMC results contributed by ETH showed greatly improved lift-off length and slightly improved ignition delay compared with a well-mixed model implemented by the same group.

Do transported PDF methods give superior results compared with well-mixed models?

UNSW found slightly improved ignition delay and greatly improved lift-off length with the PDF method for both Spray A and Spray H, and for both T_a and O_2 variations. Penn. State found greatly improved LOL and ignition delay for Spray A, but only slightly better ignition delay in spray H. (The chemistry model from spray H was more rudimentary.) Thus, PDF methods appear to improve results relative to well-mixed models. Of course, there is a significant trade-off for computational expense.

Summary of findings, discussion, and recommendations for future work

The participation was very good and everyone can be thanked for their contributions.

Definitions
Differing definitions are still a problem, particularly for the lift-off length. Since chemical sub-mechanisms for OH* are at a relatively early stage, it is generally not considered by modellers. Thus:
- It would be preferable if quantitative measurements of the ground state OH and/or other reacting scalars were available. Experience from the TNF workshop suggests that quantitative, simultaneous measurements of temperature and the major species needed to form a mixture fraction would be desirable.
- Further work is suggested to improve the kinetics of OH* and to incorporate OH* into the models.

Well-mixed combustion models
Well-mixed combustion models are attractive because they are computationally efficient and relatively straightforward to implement. The results show across the board that these models are capable of predicting basic trends. Further investigation of why this is the case seems warranted – is it that turbulent fluctuations are genuinely small or is it that the results are not sensitive to the fluctuations? They generally err on the side of over-predicting both ignition delay and lift-off length. This might be connected with the quite filamentary flames

that result in these models, which presumably lead to large rates of turbulent transport out of the reaction zone. Further analysis of the reasons for the observed trends would be useful.

It may be useful if a sub-set of the contributing groups try to converge on numerical parameters with their respective well-mixed models, in order to rule out numerical error as a reason for observed differences.

Flamelet combustion models

Relative to well-mixed models, flamelets can potentially improve modelling by improved treatment of fluctuations as characterised by non-trivial PDFs of mixture fraction, etc.. On the other hand they approximate chemistry by assuming that the thermochemical state space is very low dimensional and that it is the same as computed in a simplified counter-flow situation. Computationally, they are the most efficient of all the contributed approaches.

Although some very good results with flamelet approaches were reported, they were not consistent across the board and there was little useful information to enable a direct comparison with well-mixed models. More systematic investigations are recommended to determine the benefits and limitations of flamelet approaches.

CMC combustion models

CMC has similar advantages to flamelets with respect to treatment of fluctuations. CMC assumes the thermochemical state-space is locally one dimensional, but allows it to evolve in time and space. The results shown in ECN2 clearly show CMC is an improved model relative to a well mixed model. The computational expense is much larger, however.

TPDF combustion models

TPDF approaches have several advantages, notably treating the source term closure exactly and being quite general with respect to combustion regime. The results from ECN2 clearly show the TPDF model is an improved model compared with the well-mixed model. This comes with a price of significantly larger computational expense however, suggesting avenues to reduce the cost of this method should be investigated.

Suggested future modelling targets

ECN3 would benefit by continuing to pursue the existing target cases. Much has been learned compared with ECN1, but several issues remain outstanding and further investigation is required.

Additional target cases could consider

- Multiple injections: The situation of a single, high momentum injection is relatively straightforward for RANS. LES practitioners might be more interested in having more transient situations such as might arise in multiple injections. In addition, multiple injections might result in a more demanding test of turbulence-chemistry interaction models since the injection of new cold fuel into an already burning and mixing environment might result in different combustion behaviours.
- Larger nozzle: Those interested in heavy duty applications might be interested in a larger fuel nozzle. This could result in the regions of spray and combustion overlapping, which might result in a more demanding test of models and the need to consider spray-combustion interactions with a greater level of detail.
- Walls: With industry trends towards longer lift-off lengths, the wall is becoming increasingly important. Scenarios such as re-entrainment or heat loss at the wall might result in different combustion behaviours which models cannot yet capture.

[1] Sarathy, Mehl, Westbrook, Pitz, Togbe, Dagaut, Wang, Oehlschlaeger, Niemann, Seshadri, Veloo, Ji, Egolfopoulos, Lu, Comprehensive chemical kinetic modeling of the oxidation of 2-methylalkanes from c7 to c20, Combustion and Flame 158(12), 2011, pp. 2338–2357, Mani.Sarathy@kaust.edu.sa
[2] Lu et al. 53 species: http://www.engr.uconn.edu/~tlu/mechs/mechs.htm
[3] Seiser et al.
https://www-pls.llnl.gov/?url=science_and_technology-chemistry-combustion-nc7h16_reduced_mechanism

ECN2 Soot Session

Organizers: Emre Cenker (Duisburg/IFPEN), Dan Haworth (Penn State)

Contributors: M. Bolla and Y. Wright (ETH – Zurich); Q. Jiao, H. Wang, L. Qiu and R. Reitz (University of Wisconsin – Madison)

Summary

Soot was a new topic for ECN2, and soot measurement and modeling for ECN configurations are both in their early stages compared to spray and combustion characterization.

On the experimental side, Emre Cenker gave an overview of soot measurement issues and data that are available for the ECN configurations. The experiments targeted soot volume fraction measurements in Spray A, including variations in ambient temperature and ambient oxygen concentration, along the central axial cross section. Experiments also included the standard diagnostics to verify that the conditions corresponded to those of Spray A. A Laser Extinction Method (LEM) and Planar Laser Induced Incandescence (PLII) were coupled for quantitative spatially resolved measurements. LII images were taken after the start of injection where quasi-stationary combustion was established. In addition, by changing the LII timing relative to the injection timing, the temporal variation of the soot cloud was observed. Lift-off length measurements and flame luminosity imaging were also conducted for each boundary condition to interpret the soot measurements. Due to some inaccuracy in the Spray A characterization measurements, soot results presented at this workshop were acquired under slightly different ambient conditions compared to the nominal Spray A conditions: -1 kg/m^3 in ambient density, and +30 K in ambient temperature.

On the modeling side, Dan Haworth gave an introduction to soot physics and CFD-based soot modeling, including radiation heat transfer. Two groups submitted computed mean soot volume fraction data for Spray H (n-heptane). Both used semi-empirical two-equation soot models, but there were several important differences between the two sets of simulations. These included different gas-phase chemical mechanisms, different turbulence-chemistry interaction treatments (TCI neglected versus TCI accounted for using a CMC model), and different radiation models (radiation neglected versus radiation accounted for using an optically thin model), in addition to differences in the soot models themselves. Both models produced reasonable levels of soot compared to the experiments, and both captured the measured trends in soot volume fraction with variations in ambient O_2 level and ambient density.

Conclusions

The results on the experimental side show that Spray A is a moderately sooting jet where signal trapping is not significant, indicating greater potential for quantitative soot diagnostics. Maximum soot volume fractions of approximately 2-4 ppm are measured at near-Spray A conditions (21.8 kg/m^3, 930 K, 15% O_2), and are as high as 12 ppm at elevated temperature (1030 K). For the 1.5 ms nominal Spray A injection duration, the soot cloud remains transient. Therefore, a longer injection duration of 4 ms was used to analyze the soot structure in a quasi-steady mode. Variations of ambient temperature and oxygen concentration were carried out, and the effects on soot formation and oxidation were consistent with those in the literature.

On the modeling side, only Spray H soot results were submitted, as reliable gas-phase chemical mechanisms have been available for n-heptane for some time. Existing soot models are able to reproduce measured soot levels and trends with variations in ambient oxygen level and density for Spray H. However, because of the significant differences between the models, no definitive conclusions could be drawn regarding the relative merits of the different modeling approaches or which physical subprocesses are the most important. Some groups now are beginning to show promising combustion results for Spray A (n-dodecane) in the ignition and liftoff length session, and it is anticipated that soot modeling results should be forthcoming for Spray A.

Recommendations

- It has been shown that accuracy of ambient and boundary conditions in Spray A is crucial. It is therefore recommended that the temperature be characterized carefully and taken into account when monitoring the gas mixture of ECN pre-combustion vessels.

- Significant statistical error was observed in the present LII experiment. It was shown that jitter between the laser and the camera was very probably responsible for the majority of this error. It is therefore recommended for future ECN soot experiments to minimize the jitter and to take it into account in the LII calibration.

- For quasi-steady mode measurements, a longer injection duration such as 4 ms should be employed.

- The focus in soot modeling should shift to injectors and fuels for which new experimental measurements are being made: Spray A, in particular.

- To make progress in physical understanding and modeling, modelers should perform systematic parametric studies to isolate and quantify the effects of individual physical processes. For example, the importance of TCI (or of radiation) can be isolated by comparing results from a model that neglects TCI (or radiation) with results from a model that accounts for TCI (or radiation). The relative importance of individual soot subprocesses (e.g., nucleation, surface growth, agglomeration) can be established by varying soot model parameters.

Session summary: Engine Flows
Group leader: Sebastian Kaiser (U. Duisburg-Essen), Brian Peterson (TU. Darmstadt)
Contributors: same

Background:

At ECN1, it was proposed to add experiments in a complete engine geometry to the ECN's activities. The ECN web page already contains data from two optical engines: U. Michigan's two-valve research engine, and Sandia's four-valve hydrogen DI engine. However, the corresponding activities were not represented at ECN1 (neither experiments nor modeling), and in the case of Sandia's engine there is currently no prospect of adding to the data base. Thus, as a first step, an Engine Group was formed at ECN1. Dave Reuss presented the U. Michigan engine to this group at the Nov. 2011 group web meeting.

One of the salient features of ECN target experiments is that they can be performed in multiple locations. In the case of engines, this is difficult to achieve. At both the Nov. 2011 web meeting and the Jan. 2012 ECN 1.1 web conference discussion of the importance of such "multiplicity of location" was a prominent part of the session. Since agreement on a particular engine geometry seems unlikely in the near future, at ECN 1.1 a standardized experiment was proposed. The experiment consists of measuring the velocity field in the central vertical plane of the motored engine using PIV. Detailed specification of the boundary conditions and data acquisition to be used were distributed after ECN 1.1, can be requested from sebastian.kaiser@uni-due.de, and will be posted in the engine group's space on the ECN web site at https://share.sandia.gov//ecnwg/engineflow/. Most of the specs are also on slides 9 and 10 of the ECN2 engine flow presentation.

Session

Sebastian Kaiser summarized past activities and current situation of the ECN's engine group and presented the standardized flow experiment. Three universities had expressed interest in contributing to the flow experiment: U. College of London, TU Darmstadt (TUD), U. Duisburg-Essen (UDE). At the time of ECN2, contributions from the last two were available. Brian Peterson from TU Darmstadt presented the results.

Apart from different engine geometries (bore and stoke very similar, heads are different but both 4V pentroof, CR 8.5 at TUD, 10 at UDE), the experiments differed in intake pressure (0.7 bar at TUD, as specified, but 1.0 bar at UDE).

During the intake stroke, mean velocity fields are similar in pattern between the two engines, with velocity magnitudes higher in the UDE engine. The RMS is also higher at UDE. The general similarity in mean-flow pattern persists throughout the compression stroke, but now velocity magnitudes are higher at TUD, while the RMS continues to be higher at UDE. A physical explanation for the qualitative differences was not found.

In the ensuing discussion, N. Peters remarked that tumble is a bad flow for such a cross-platform comparison, since it is known to be highly unstable, potentially amplifying small differences in boundary conditions. S. Kaiser considered this consistent with the fact that in diesel-engine simulations, where the flow generally is swirling, the simple assumption of solid-body rotation towards the end of compression has had remarkable success.

V. Sick warned of any cross-engine comparison and suggested a major contribution of the ECN's engine activities could be to identify the essential questions in the field.

Another member of the audience reminded that part of the TNF’s success lies in having a hierarchy of experiments, which transferred to the ECN’s engine group may mean having simpler experiments than those in an actual engine, for example flow below a single intake or a whole head on a flow bench. Several members of the audience commented that such arrangements were too simplistic.

The presenters again invited all interested parties to perform the standardized experiment and thereby contribute to an initial data base. UDE will repeat the experiment at the “correct” intake pressure of 0.7 bar. No communally agreed conclusion on other future steps was reached.

Andreas Dreizler (TU Darmstadt) and Sebastian Kaiser further asked who from the modeling side would be interested in modeling such engine data as what was presented at ECN 2. A fair number of groups expressed interest, but no final commitment was made. Sibendu Som (Argonne Nat’l Lab) expressed that additional information about EGR and temperature would be needed to for modeling (EGR when operating fired).

Gasoline Spray Session

Session Organizer: Scott E. Parrish, General Motors R&D

One outcome of the first ECN workshop was the decision to form a gasoline spray working group. This group has formed and has had some activities since ECN1 including two WebEx meetings and an informal meeting at the 2012 SAE world Congress. The primary focus of the group thus far has been to determine an appropriate injector specification and to identify an injector supplier able to meet the needs of the group.

It is intended that the findings of the group will be transferable and relevant to *future advanced* engines. Therefore in specifying an injector it is important to keep in mind the spray requirements of advanced applications such as stratified spray-guided and down size boosted diluted combustion systems. The interaction of adjacent spray plumes is of great importance to both current and advanced gasoline applications. Factors that affect spray plume interaction include: spray pattern, L/D ratio, hole manufacturing method, and the proximity of the holes on the nozzle. The proper combination of all of these parameters is required for successful mixture preparation.

After considerable debate the following injector specification was selected: solenoid actuated, 80 degree spray angle, 8-hole, circular pattern, stepped hole VCO, no bend angle, straight EDM holes, and a flow rate of 15 cc/s @ 10 MPa fuel pressure.

The needs from the injector supplier have been identified and include: 12 injectors and 6 injector drivers along with 6 simplified wiring harnesses. The supplier must also agree to allow detailed geometric measurements and to supply a CAD model of the injector nozzle to support internal flow modeling activities. Four injector suppliers (Bosch, Continental, Delphi, and Magneti Marelli) were solicited and all expressed interest in participating. After considerable contemplation, Delphi was the supplier selected do to the fact that they were willing to accommodate nearly all the desires of the group. The selection of Delphi is NOT an endorsement or an indication of hardware superiority but rather more to do with convenience.

The majority of the session was devoted to the presentation of hardware details. In addition to injectors and injector drivers, Delphi will be providing provisions to mount the injector and to attach a fuel line. These parts will include a cast rail socket and a fastening clip. Details of each part were discussed and critical dimensions were presented. Pictures and drawings facilitated the discussion. A solid model of the nozzle seat was shown and a CAD model will be available to the group upon the nozzle design being finalized. Spray patternation results of an 8-hole development nozzle were shown and exhibited good symmetry.

In preparation for performing measurements, experimental conditions were discussed and the following conditions were proposed. Fluid, Iso-Octane; injection pressure, 20MPa; fuel temperature, 90 C; ambient pressure, 6 bar; ambient temperature, 300 C; and injected mass, 10 mg.

Last Session: Birdie-vortex interaction in strongly accelerated flows

As the case for ECN1, this last session of the workshop was by far the most interesting and important! In order to better understand the impact of the outcomes of this session it is necessary to recall the context. ECN1 had ended with a crucial session focussing on the experimental study of droplet breakup theory on San Buenaventura State Beach. Although of great interest, this session had failed to achieve the objectives of understanding the mechanisms mainly because of uncertainty issues and of the complexity of the configuration where multiphase issues were added to turbulence droplet interaction in supercritical conditions (the so called tube roll up pressure effect). It was therefore decided for ECN2 to simplify the configuration and enable more precise measurements in order to aim a final complete understanding. The simplification consisted in using the nowadays well known gas analogy where the problem is treated in pure gas phase. Of course, to ensure some degree of representation of the final application configuration, the liquid phase was still present since the experiment was conducted on the river side of the Neckar river, but it was verified that the latter remained laminar during the time of the experiment.

The more motivated participants of the conference therefore joined the grass fields of the Neckar river sides on this sunny afternoon. The first step was installation of the experimental setup consisting of high precision badminton sets. At least 5 different setups were installed with different orientations to enable side-by-side comparison of experimental results and therefore account for possible differences in initial conditions related to wind direction. Additional experimental complications due to knot-making were bypassed by the expertise of clever PhD students.

It was found that the badminton configuration was well adapted to side-by-side comparisons. The quantity that could be compared is not yet completely understood, but it was still considered as an interesting first step (experimentalist are pragmatic people). Unfortunately, uncertainty issues related to the position of the field border could not be completely avoided, in particular, because of the presence of French people. Also the possibility of high entropy generation induced by birdie deformation phenomena was identified as a possible source of uncertainty.

Despite these experimental difficulties, a final experiment was carried out allowing direct comparison of measurement precision of Sandia and IFPEN labs. The outcome of this experiment is considered by the ECN as a major breakthrough in the world of science. Indeed, even if it is not bound to happen again, it was found that IFPEN had a much better precision than Sandia. This result is so striking that a publication in "Nature" is under submission by the ECN with very strong proponents of the cause from IFPEN!

Concerning the simulation side, well as usual the main outcome of the session was a parametric study of the different liquid mixtures available on the grass (fruit juices, beer of all origins...), and of the different position to test those mixtures (laid down in the grass, sitting on the left or right side, facing the sun or in the shade...). But as a good example of the ECN spirit, experimentalist and modellers all came to join the effort in this challenging activity. Therefore it was decided that this session should again absolutely be renewed in the next workshop, to finally try to come up with a conclusion!

ECN2

2nd Workshop on Spray Combustion

Heidelberg, Germany ■ 7-8 September 2012

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