# ECN5 TOPIC 3 – EVAPORATIVE DIESEL SPRAY SUBMISSION GUIDELINES

Version 160603

# CONTENTS

## 1 INTRODUCTION

The main focus of the activities of the present topic is the inert spray development, in continuation of the topic 3 of ECN4, *Vaporizing spray*. Inherent experimental and computational results concerning Spray A, Spray C and D will be analyzed and discussed in this topic.

The analysis will be focused on the metrics related to the inert spray development including i.e. liquid and vapor phase penetration, spreading angle, mixture fraction and velocities.

Additionally, this workgroup aims to be the reference for the research groups participating in topic 4 and topic 5, serving as a platform for the comparison of the inert field “feeding” the model.

# 2 OBJECTIVES

## 2.1 Experimental objectives

Here below, a list of the main focuses that are proposed to the experimental contributors:

- Corroborate the Spray C/D database
- Increase the available data concerning multiple injections
- Continue the discussion concerning the liquid phase measurement implementing the recent improvements to the DBI setup.

In addition, the following challenges are proposed, seeking for new experimental approaches and data analysis:

- The imaging diagnostics put in place present a huge number of information that are normally condensed in one or two global parameters. Are there other information in the images which can be helpful to characterize the spray? (i.e. boundaries fluctuation frequencies, liquid length transients…)
- Are there other diagnostics (apart from Rayleigh scattering) capable of giving quantitative data about the spray mixing field for spray A? (i.e. UV-VIS light absorption-scattering).

## 2.2 Modeling objectives

The objective of the topic is to evaluate the models predicting capabilities at reference conditions and through the parametric variations proposed.
For a comprehensive and constructive evaluation of the model the following recommendations are issued:

- Perform the simulation on the higher possible number of parametric variations. This would limit the one-case “model tuning”
- Provide a complete set of data including also mixing and velocity field (see appendix 2)
- Following the data formatting proposed in these guidelines. This would boost significantly the exchange between different groups.

The understanding of the effect of cavitation, discernible when comparing the experimental data of spray C and D injector, is posed as an important new reference for modelers.
At the same time the availability of new mixing field experimental data (Sandia – time resolved Rayleigh scattering) wants to stimulate CFD contributors to focus on mixing field transient and time/spatial fluctuations.

In order to make a step towards topic 2 a specific additional objective is proposed: to investigate the impact of the breakup constants on the spray global structure.

Interaction with the following topics will be needed: topic 3 should serve as a platform to compare the transient mixing field that is "used" to pre-compare the models participating to the "reacting topics" (Topic 4, 5 and 6). To this end a pre-deadline is proposed (1st October) and the metrics to be evaluated for the pre-comparison will be soon notified.

## 2.3 Analysis objectives

Based upon the interaction between both experiments and modeling, understanding of the spray formation process should be gained according to the following objectives:

- Moving towards topic 2: Fill the gap between *near* field and spray macroscopic feature. Putting together experimental results (X-ray Absorption and Rayleigh scattering) and modeling results.
- Investigate the transient (during the spray development) and time/spatial fluctuations of the mixing field taking place within the spray. Taking advantage of the high speed techniques (quantitative e.g. Rayleigh scattering but also qualitative e.g. DBI or Mie), try to bring further the comparison between experiments and modeling results.
- A detailed comparison between Spray A/C/D will be performed, to assess the effect of nozzle size on spray development.
- Investigate the effect of cavitation on spray development by comparing in detail the data from spray C/D.

# 3 TARGET CONDITIONS

Target conditions will be defined in terms of a nozzle, injection and ambient conditions. The reference ambient conditions will be the same as in ECN4, as shown in Table 1:

| Parametric Variable | ACRONYM | O2 [%] | Ta [K] | Dens [kg/m3] | Pinj [MPa] | Inj Duration |
|---|---|---|---|---|---|---|
| Standard Spray "A" | Ai | 0 | 900 | 22.8 | 150 | SHORT/LONG/SHORT2 |
| Standard Spray "A" | Ar | 15 | 900 | 22.8 | 150 | LONG |
| Temperature | AisoTi | 0 | 300 | 22.8 | 150 | LONG |
| | AT0i | 0 | 440 | 22.8 | 150 | LONG |
| | T2i | 0 | 800 | 22.8 | 150 | LONG |
| | T3i | 0 | 700 | 22.8 | 150 | LONG |
| | T4i | 0 | 1000 | 22.8 | 150 | LONG |
| | T5i | 0 | 1100 | 22.8 | 150 | LONG |
| Density | D1i | 0 | 900 | 15.2 | 150 | LONG |
| | D2i | 0 | 900 | 7.6 | 150 | LONG |
| Injection Pressure | P1i | 0 | 900 | 22.8 | 100 | LONG |
| | P2i | 0 | 900 | 22.8 | 50 | LONG |
| Pilot injection | MAIi | 0 | 900 | 22.8 | 150 | **0.5 ms pulse - 0.5 ms dwell - 0.5 ms pulse** |

*Table 1 – Nomenclature for submission of Topic 3 Spray A parametric variations.*

The letter "i" after each test condition acronym indicate the *inert* tests (0% oxygen) in contrast with the tests at reacting conditions. The nomenclature aims at being consistent with the one used in topic 4 and5.
Naming for the injection actual duration will be:

- SHORT = 1.5 ms. This duration is the standard Spray A injection duration.
- LONG = 5.0 ms. This duration will be the reference for the analysis of liquid length stabilization, so that steady spray conditions are achieved.
- SHORT2 = 0.5 ms. This duration will be used as a reference for multiple injection studies.

To simplify data handling, the nomenclature of a given experimental condition for single injection cases will be:

NOZZLE – OPERATING CONDITION – INJECTION DURATION

While for multiple injection cases the nomenclature will be simplified to:

NOZZLE – OPERATING CONDITION

For example, a test with Spray A injector for the reference inert/reacting condition will be named as:

A-Ai-LONG
A-Ar-LONG

While the same operating conditions for Spray C injector will be named as:

C-Ai-LONG
D-Ar-LONG

More specific directions on file naming conventions can be found in Appendices.

Target injector for Spray A will be nozzle 675 in terms of modeling efforts, although experimental contributions from other injectors are also welcome.

For spray C and D the target injector are respectively Nozzle #037 and #134 the characteristics and reference data are reported in Table 2

| Nozzle Type | Ref Noz | Ref Nozzle Diameter | Ref Mass Flow Rate | Hydraulic parameters (Ca, Cv..) | Reference results (VP, LP, velocities, Mixing) |
|---|---|---|---|---|---|
| Spray A | 675 | 93 (APS 7BM) 89.4 (µscope) | CMT VIM | Available and described in AAS 22(12), 1011-1052 | VP and LP available from Sandia/IFPEN CMT/Tue etc. Available mixing field for 677 and velocities for (IFPEN exp to be checked). |
| Spray C | 037 | 207 (APS 7BM) 208 (µscope) | Measured by CMT Payri et al, Fuel 180 (2016) A reference educated injection rate is provided at http://www.cmt.upv.es/ECN05.aspx | | Available VP and LP in Westlye et al SAE 2016-01-0860 And Payri et al http://doi.org/10.1016/j.enconman.2016.07.077 Lift-off and Ignition delay in Payri et al. http://doi.org/10.1016/j.enconman.2016.07.079 |
| Spray D | 134 | 188 (APS 7BM) 188 (µscope) | | | |

*Table 2 – Reference nozzle and data.*

# 4 PARTICULAR RECOMMENDATIONS FOR CALCULATIONS

When performing calculation, the following indications have to be followed:

- INJECTION RATE: Mass flow rate at the nozzle exit from virtual ROI tool from CMT and measured nozzle coefficients (http://www.cmt.upv.es/ECN03.aspx). For Spray C/D injectors an educated mass flow rate will be provided as soon as possible. In case please contact michele.bardi@ifpen.fr
- MINIMUM GRID SIZE: Each contributing group can use a preferred grid to perform any of the requested calculations. However, a minimum grid size of 0.25 mm is required for all submissions.
- MODEL CONSTANTS: Each contributing group should use the same model constants across all simulations (parametric variations, Spray A, B, C, D, etc.).
- TESTS CONDITIONS: for a comprehensive evaluation of the model results the simulation of only one test condition is probably not enough. Whenever possible is strongly suggested to simulate at least one parametric variation and id possible all of them.

## 4.1 Comparability of mixture fields

To enable a meaningful comparison among different modeling submissions  metrics such as liquid penetration and liquid volume fraction must be analyzed using consistent calculation methods.

For that purpose, participants will have to submit at least the following information:

- Spray Tip penetration and maximum liquid length according to the instructions in the appendix.
- 2D maps of the following variables

| Data | ACRONYM |
|---|---|
| Axial velocity (m) | U |
| Radial velocity (m) | V |
| Mixture fraction | Z |
| Temperature (K) | T |
| Density (kg/m$^3$) | RHO |
| Mixture fraction variance | Zvar |
| Turbulence kinetic energy (m$^2$/s$^2$) | K |
| Turbulence kinetic energy dissipation rate (m$^2$/s$^3$) | EPS |

*Table 3 – 2D-resolved data required from comparison of spray mixture distribution from modeling*

The following conventions should be met:

- 2D (axial-radial) Favre-averaged fields (ensemble averaged if Favre average impossible)

- Spatial discretization: Variables should be interpolated onto a uniform Cartesian mesh with the following discretization
    - Radial: 0 to 20mm; 0.04mm spacing (501 points)
    - Axial: 0 to 100mm; 0.2mm spacing (501 points)
      (if using a smaller mesh, the spacing should be maintained).
- Time discretization: from 100μs to 1500μs After Start of Injection, each 100μs.

After the comparison is performed, those groups with large departures from the mixing field will have to review their spray models.

## 5 DEADLINES

The following deadlines have been established:

- Modeling results for Spray A inert spray to be used for topic 4 and 5: October 1st 2016.
- Experimental and modeling results for reacting conditions: January 15th, 2016.

# 6 PARTICIPANT LIST

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*Table 4 – Participant list*

(*) Topic coordination

# APPENDICES

# 7 APPENDIX 1 – SUBMISSION OF EXPERIMENTAL RESULTS

## 7.1 Spray metrics and variable definition

The following definitions should be used for the calculation of the spray metrics (for further information check standardization at info at http://www.sandia.gov/ecn/cvdata/expDiag.php). In the following table the techniques to be employed, and the related metrics are indicated for reference.

| TYPE | SPRAY METRIC | ACRONYM | TECHNIQUE | DEFINITION |
|---|---|---|---|---|
| Global | Liquid length (steady) [mm] | LL | Diffused backlit illumination | Extinction profile of the average image + Extinction deacay extrapolation.<br>As described by Manin Et AL COMODIA 2012<br>Averaging time window 2-4 ms ASOI |
| Time resolved | Liquid phase penetration [mm] | LP | Diffused backlit illumination | Light extinction threshold (0.6)<br>Leading edge of the contour. |
| | Vapor phase penetration [mm] | Si/Sr | Schlieren (Mie at non evaporative conditions -max 400 K) | Image processing available on ECN web page |
| 2D maps | Light extinction [-] | tau | Diffused backlit illumination | Calculated following the Beer-Lambert law<br>Averaging time window 2-4 ms ASOI<br>tau = -ln(I/Ibg) |

*Table 5 – Experimental definition of Spray metrics*

Whenever possible, spray metrics obtained after processing of raw information should be submitted. More details on the standard processing routines can be found at the ECN site (http://www.sandia.gov/ecn/cvdata/expDiag.php ).

The file name depends on the type of information to be submitted

- **Global indicators:** A template Excel file will be provided by coordinators, where only the corresponding values for experimental indicators will be included. The name of the file will follow the structure:

ECN5E_[GROUP]_GLOBAL_[INJECTOR].xls

- **Time-resolved information:** Only one ASCII plain text file per operating condition and spray metric will be sent. It will contain three columns, the first one with the time (ms), and the second and third with the average and uncertainty of the corresponding measurement. Name and units should be indicated at the first raw. File name should follow the structure:
  ECN5E_[GROUP]_[VAR]_[INJECTOR]_[COND]_[DUR].txt

The following nomenclature has been applied for file names

- ECN5E identifies the information as an experimental contribution.
- GLOBAL identifies the file as containing Global Combustion Indicators.
- [GROUP] is a string for the submitting group acronym , e.g. TUE
- [VAR] is a string for the submitted combustion indicator Acronym according to the corresponding column in Table 5.
- [INJECTOR] is a string for the Nozzle + Injector reference number.
- [COND] is a string for the ambient condition according to Table 5
- [DUR] is a string for the injection duration coding as indicated in Section 3 (LONG/SHORT/SHORT2).

Examples:

- ECN5E_IFP_GLOBAL_SA210675.XLS would be a submission from IFP of global indicators obtained in experiments with SA nozzle, injector number 675.

- ECN5E_IFP_GLOBAL_SC210003.XLS would be a submission from IFP of global indicators obtained in experiments with SC nozzle, injector number 210003.

- ECN5E_IFP_Si_SA210675_Ai_LONG.txt would be a submission from IFP of the inert tip penetration for Spray A injector 675, nominal operating conditions (ambient conditions Ai in Table 1) and LONG injection duration.

- ECN5E_IFP_Si_ SC210003_Ai_LONG.txt would be a submission from IFP of the reacting tip penetration for Spray C injector 210003, nominal operating conditions (ambient conditions Ai in **Error! Reference source not found.** 1) and LONG injection duration.

- **Spatial- (and time-) resolved variables**

For space and time-resolved information (i.e. imaging experiments) ensemble-averaged information is in general preferred. If possible, standard deviation and sample size (number of injection cycles) should be delivered for each measured parameter.
The time averaged window suggested is from 2 to 4 ms ASOI

Whenever possible, a high acquisition rate for experimental should be used (e.g. high speed imaging at rates higher than 20000 fps) so that information is produced at as many time instants as possible. However, if this is not feasible, acquisition should priorize the following timings (in ms ASOI):

- Steady spray 4.5 ms
- Transient spray penetration: 0.5 – 1 - 2 ms

It is recommended that data is submitted following the format employed for Rayleigh scattering results shown in
http://www.sandia.gov/ecn/cvdata/assets/Rayleigh/bkldaAL4mixing.php
either as a 16-bit png image (with an indication of the maximum value in Physical Units of the corresponding variable, maxImg) or as a zipped ASCII plain text file with accompanying injector coordinates and a vector of axial and radial positions.

File name will follow the convention

ECN5E_[GROUP]_[VAR]_[INJECTOR]_[COND]_[DUR]_[t].png
ECN5E_[GROUP]_[VAR]_[INJECTOR]_[COND]_[DUR]_[t].txt

The following nomenclature has been applied for file names

- ECN5E identifies the information as an experimental contribution.
- [GROUP] is a string for the submitting group acronym , e.g. IFP
- [VAR] is a string describing the corresponding measured variable. This should be agreed with the Topic coordinator before submission.
- [INJECTOR] is a string for the Nozzle + Injector reference number.
- [COND] is a string for the ambient condition according to Table 1.
- [DUR] is a string for the injection duration coding as indicated in Section 3 (LONG/SHORT/SHORT2).
- [t] is a string for the particular timing, in μs after Start of Injection (ASOI).

Example:

- ECN5E_IFP_EXT_SA210675_T1i_LONG_4000.txt would be a submission from IFP of the liquid phase extinction at 4000 us for Spray A injector 210675, Temperature parametric variation at inert conditions (ambient conditions T2i in Table 1 and LONG injection duration.

Attached to each submission, a text file summarizing the particular experimental techniques that have been used has to be sent.

# 8 APPENDIX 2 – SUBMISSION OF MODELING RESULTS

## 8.1 Global and Time-resolved Combustion Indicators

The following definitions will be used for the modeling-based combustion indicators:

| TYPE | SPRAY METRIC | ACRONYM | DEFINITION |
|---|---|---|---|
| Global | Liquid length (steady) [mm] | LL | Definition: furthest axial position from the nozzle where the path-averaged liquid volume fraction through a 0.5-mm x 0.5-mm path through the spray is 0.15%.<br>Computation: For each 0.1-mm x 0.1-mm data cell, average the 2-D computed Path-Averaged Liquid Volume Fraction for 2 cells surrounding the target cell in each direction (generating an effective 0.5-mm x 0.5-mm averaging area). Time average between 2-4 ms ASOI |
| Time resolved | Liquid phase penetration [mm] | LP | Definition: furthest axial position from the nozzle where the path-averaged liquid volume fraction through a 0.5-mm x 0.5-mm path through the spray is 0.15%.<br>Computation: For each 0.1-mm x 0.1-mm data cell, average the 2-D computed Path-Averaged Liquid Volume Fraction for 2 cells surrounding the target cell in each direction (generating an effective 0.5-mm x 0.5-mm averaging area). |
| | Vapor phase penetration [mm] | Si/Sr | Definition: furthest axial position from the nozzle where the fuel mass fraction is 0.1%. |
| 2D maps | Vapor Mixture Fraction [-] | | Local vapor-phase mixture fraction at a 2-D plane along the spray centerline. |
| | Path-Averaged Liquid Volume Fraction [-] | LVF | Integrate the total liquid volume fraction in each data cell (0.1 mm x 0.1 mm face area) through the depth of the spray, collapsing the liquid volume fraction field to a 2-D map. For 2-D computations, assume axial-symmetry and then integrate. The path-averaged liquid volume fraction should then be obtained by dividing the path-integrated liquid volume fraction by the path length along which liquid is present. |

| | | | |
|---|---|---|---|
| | Path-Averaged Droplet Number Density [1/m$^3$] | N | Integrate the total number of droplets in each data cell (0.1 mm x 0.1 mm face area) through the depth of the spray, collapsing the number density field to a 2-D map. For 2-D computations, assume axisymmetry and then integrate. The path-averaged number density [1/m3] should then be obtained by dividing the path-integrated total number of droplets by the path length along which liquid is present. |
| | Path-Averaged Sauter Mean Diameter [μm] | SMD | The Integrated liquid volume and the integrated liquid surface area through the depth of the spray should be calculated, collapsing the values to a 2-D map. Then, the SMD 2D Map is obtained as the ratio between the two previous 2D-maps (Path integrated volume/Path integrated surface area ) |
| | Projected Liquid Mass Density [μg/mm$^2$] | PMD | This quantity is desired for the non-evaporating (300 K) Spray A case, for comparison against x-ray data. Projected mass density [μg/mm2] should be calculated by determining the apparent liquid density within each data cell (0.1 mm x 0.1 mm face area), integrated through the depth of the spray |
| | Axial Velocity [m/s] | U | Local vapor-phase axial velocity at a 2-D plane along the spray centerline |
| | Temperature [K] | T | Local vapor-phase temperature at a 2-D plane along the spray centerline |

*Table 6 – Modeling definition of Spray metrics*

Whenever possible, spray metrics obtained after processing of raw information should be submitted. Details on the standard processing routines can be found at the ECN site (http://www.sandia.gov/ecn/cvdata/expDiag.php ).
The file naming and the same data format employed for the experimental data should be used. (see previous section).

## 8.2 Spatial- (and time-) resolved variables

Full 2D (axial and radial) maps of following modeling-derived variables should be submitted for analyses:

The following conventions should be met:

- 2D (axial-radial) Favre-averaged fields (ensemble averaged if Favre average is not possible)
- Spatial discretization: Variables should be interpolated onto a uniform Cartesian mesh with the following discretization
  - Radial: 0 to 20mm; 0.04mm spacing (501 points)
  - Axial: 0 to 100mm; 0.2mm spacing (501 points)
    (if using a smaller mesh, the spacing should be maintained).
- Time discretization:
  - For LONG injection cases from 100μs to 7000μs After Start of Injection, each 100μs.
  - For SHORT injection cases from 100μs to 1700μs After Start of Injection, each 100μs.
  - For multiple injection cases, from 100μs to 2000μs After Start of Injection, each 100μs.

DATA FILE STRUCTURE

The data have to be submitted as ASCII plain text. The first line should include the variables name according to the nomenclature in Table 6. To enable post-processing, each file line should contain all variables related to one position. The final structure will be:

```
x[m],r[m],U[m/s],V[m/s],Z[-],T[K],RHO[kg/m3],YC12…
x1,r1,u,v,Z,T,RHO,n-dodec…
x2,r1,u,v,Z,T,RHO,n-dodec…
…
xn,r1,u,v,Z,T,RHO,n-dodec…
x1,r2,u,v,Z,T,RHO,n-dodec…
...
```

Files are expected to be organized in directories such as:

ECN5M_[GROUP]_[INJECTOR]_[COND]_[DUR]

within which individual files should be named:

ECN5M_[GROUP]_[INJECTOR]_[COND]_[DUR]_[t].txt

The following nomenclature has been applied for file names

- ECN5M identifies the information as a modeling contribution.
- [GROUP] is a string for the submitting group acronym.
- [INJECTOR] is a string for the Nozzle + Injector reference number.
- [COND] is a string for the operating condition according to Table 1.

- [DUR] is a string for the injection duration coding as indicated in Section 3 (LONG/SHORT).
- [t] is a string for the particular timing, in μs after Start of Injection (ASOI).

The previous file directory should be submitted in a single compressed file.

Examples of directory/file names:
ECN5M_IFP_SA201675_Ai_LONG/ECN5M_IFP_SA210675_Ai_LONG_1000.txt
ECN5M_IFP_SA201675_Ai_LONG/ECN5M_IFP_SA210675_Ai_LONG_4000.txt

corresponds to a submission from IFP of CFD modeling results at 1.0/4.0 ms ASOI for injector 675, operating conditions of spray A (ambient conditions Ai in Table 1**Error! Reference source not found.**) and LONG injection duration.

MODELING SETUP DESCRIPTION
In addition to the data files, an Excel file should be submitted summarizing the information on the particular model:

| PARAMETER | DESCRIPTION EXAMPLES |
|---|---|
| Code name | KIVA, OpenFOAM, CONVERGE, Fluent, … |
| Turbulence model | RANS, k-ε, LES etc. |
| Sub-grid or turbulent scalar transport | gradient transport |
| **Spray model** | |
| Used Lagrangian discrete phase model (Y/N), If N, then what method? | Y,N |
| Injection | Blob, |
| Atomization & Breakup | KH-RT (with/without break-up length), Huh, KH, Reitz-Diwakar, ... |
| Collision | None, O'Rourke, … |
| Drag | Dynamic,… |
| Evaporation | Spalding, … |
| Heat Transfer | Ranz-Marshall, … |
| Dispersion | None, Stochastic, … |
| **Grid** | |
| Dimensionality | e.g. Full-3D domain, 2D axisymmetric, etc |

| | |
|---|---|
| Type | e.g. Block structured Cartesian, structured AMR, unstructured, etc |
| Grid size range (mm) | e.g. 0.25 mm - 5mm, … |
| Total grid number | eg 100,000 |
| **Time advancement** | |
| Time discretisation scheme | e.g. SIMPLE, PISO, etc |
| Time-step (sec) | 5e-7, variable with max Courant number equal to…, … |

*Table 7 – Modeling setup description table*