**ECN9 Ammonia topic session summary**

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The ammonia topic was included for the first time within an ECN workshop, after a decision made in the ECN8 future direction session. Two different directions were identified, resulting in two different sub-sessions within the topic.

**GASOLINE-LIKE AMMONIA SPRAYS**

The GDI-type injection session was conceived targeting SI engines applications. In-cylinder injection of ammonia at pressures up to 200 bar is considered sufficient to produce an ignitable mixture at spark timing, without considering any chemical or thermal boost. The session was split into two sub-sessions, one on sprays, and one on SI engine ignition and combustion.

The **ammonia sprays** were studied using different hardware, ranging from existing spray G eight-hole and more recent spray M eight-hole, up to a Bosch seven-hole GDI injector, and lastly up to an M variant with a single-hole nozzle, called M-SH.

The single-hole M-SH is an interesting configuration in which more fundamental observations and model validations can be conducted. A main feature of an ammonia spray is that it easily undergoes flash-boiling, therefore primary atomization is of utmost importance and scarcely studied, so far, especially for ammonia.

Different institutions contributed to the session. U-Orleans was the only institution to provide experimental measurements (morphology, droplet diameters, cone angles, penetrations).   
U-Perugia, IFP-EN, U-Mass, U-L'Aquila, U-Oviedo and PoliMI submitted simulations results, into two main categories, near-nozzle single-fluid Eulerian simulations and full-spray Lagrangian spray simulations.

Main findings and conclusions are as follows:

* Nozzle hydraulic characterization is still missing: ROI were only estimated or computed, but no data is available. This is highly desirable for the next workshop.
* Flash boiling effect on near-exit cone angle has been explored. A video dataset is available on M SH, and some data on multi-hole with jet-to-jet interaction. A quantitative assessment is needed for a future workshop. Meanwhile, models showed promising capability of capturing flash-boiling effects at various Psat(T)/Pamb ratios. New model developments or calibration of existing ones are still in progress. Consistent and detailed validations are needed.
* The single-hole M-SH injector will be selected for further studies.
* A smaller number of operating conditions will be defined (a consensus was not reached yet) as target conditions for the next ECN workshop.

In the **SI combustion** sub-session U-Orleans engine combustion experiments were presented. SI ignition of premixed ammonia can be obtained at phi=1.0-1.1, with naturally aspirated or boosted intake pressure. Throttled conditions are unfavourable, and generally ignition is not possible. H2 addition is a booster. For pure ammonia enhanced compression ratio is needed compared to typical SI engines. Advanced igniters, such as pre-chamber are also useful.

Concerning ammonia direct injection (DI), high flow-rate injectors are needed for the low stoichiometric air-fuel ratio. Strong flash-boiling occurs, which modifies spray shapes compared to classical gasoline sprays, and also local temperatures become very low.

DI injection is marginally better than PFI (premixed), but emissions (NH3, N2O, NOx, ...) remain an issue. Early SOI timings leading to “homogeneous” mixtures were better than late injections with stratified mixtures. Many points remain open for future research, such as pre-sparks to produce H2 via partial molecule cracking.

The main conclusion is that stoichiometric or slightly rich conditions will be needed for adequate combustion. Emissions and aftertreatment might dictate other directions, but it is not known now.

**DIESEL-LIKE AMMONIA SPRAYS**

This session dealt with direct injection high pressure sprays using Diesel-like hardware, and exploring the possibility of a high-pressure spray flame configuration. Guidelines requested both inert and reacting configurations using a Spray-D nozzle and operating conditions divided into two sections:

* For inert sprays, conditions following ECN recommendations were requested to explore spray mixing and evaporation.
* For reacting sprays, a higher air temperature (1200/1300K) and ambient air oxygen were chosen to explore the possibility of autoigniting configurations.

As for the inert spray study, only CMT contributed with some experimental conditions from a recent work following ECN standards but with a larger (300 um) diameter nozzle. Aside from security measures, the most challenging issue was the stable operation of the injector with ammonia, which was achieved only up to 800 bar rail pressure by increasing return flow backpressure as well as by strong cooling of the injector holder. Results hint at a mixing-controlled behaviour of ammonia sprays with an initial spray tip development which was pretty linear and quite different of that of diesel fuel with the same injector.

As for the reacting part, modelling contributions were made by TUe and PoliMi, no experiments were reported. Results showed that a stabilized flame can only be achieved at 1300K ambient air temperature, with a relatively long (2 ms) ignition delay. 1200K showed ignition at 5 ms. Results from both institutions were quite in agreement, although trends between both conditions were different.

During the discussion, the exploration of ammonia high-pressure combustion chemical mechanisms was identified as an important topic. In any case, measurement of rate of injection is a most relevant activity to feed proper boundary conditions for simulations.

**BREAKOUT – FUTURE DIRECTIONS**

During the breakout sessions, discussion was held on the two initial paths:

For Gasoline-like sprays work will be focused on spray M single-hole only to avoid having too many targets. In depth study of flash boiling is mandatory for those configurations. This configuration also seems to be a good test case for stationary combustors.

For Diesel-like sprays, spray D remains as the main injector. Ignition at >1300 K could be an option, but it seems not feasible for engines. A dual fuel configuration (diesel-like pilot to ignite the ammonia spray) could be interesting.