SCReaming for Low Emissions

Development of Selective Catalytic Reduction (SCR) Systems
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Emission standards soon to be introduced worldwide will make it necessary to reduce NO\textsubscript{X} and CO\textsubscript{2} emissions in mobile applications ranging from passenger cars to heavy-duty trucks. Technologically speaking, the most favorable way to comply with future standards is to lower NO\textsubscript{X} emissions by selective catalytic reduction (SCR) which, in thermodynamic terms, allows the lean-burn engine to operate at the best level of efficiency.

Integrating SCR technology, however, demands an approach that embraces the entire system because it involves incorporating various components in existing vehicle platforms. These components are the tank/reservoir containing the reductant used for converting emitted NO\textsubscript{X} into nitrogen, a dosing system (including pump, heated or insulated lines and pipes plus injector), a control unit, either of a stand-alone type or virtually integrated to the engine control unit, sensors for model-based control and diagnosis as well as a modified exhaust line with the actual SCR catalyst and a variety of measures for optimizing flow (e.g. mixer, inlet cones).

IAV’s strength lies in its ability to cover the entire development process from detailed component level through to validating the entire system for production.

IAV is also setting new trends in hot-end NO\textsubscript{X} aftertreatment. Systems being developed for the future are focusing on water-cooled injectors and integrated catalyst technologies, such as SCR/DPF. Gaseous-ammonia systems are being developed too.

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Simulation of Exhaust Aftertreatment Systems

1D Simulation
For efficiency reasons, the initial exhaust aftertreatment concept for any application is assessed in detail by means of validated simulation. This provides the basis for laying the exhaust line and specifying the catalysts to be used.
- Input data from engine and/or synthetic-gas test bench
- Modeling of SCR formulations taking into account catalyst aging
- Modeling of integrated SCR/DPF formulations including soot impact
- Simulation of heat transfer and heat losses
- Transient NO\textsubscript{x} conversion and NO/NO\textsubscript{2} feed-gas modeling
- State-of-the-art simulation tools (e.g. Axisuite from Exothermia\textsuperscript{®})

3D kinetic simulation
As the exhaust and reductant flow distribution at the catalyst inlet play a key part in determining SCR efficiency, three-dimensional simulation is also necessary.
- CFD flow computation for feeding into kinetic simulations
- Integration of non-uniform flow distribution in kinetic simulation
- Integration of SCR in DPF requires 3D modeling

Software in the loop
The development of dosing-control and diagnostic algorithms requires fast models that are capable of running in the control unit. These new algorithms are calibrated and validated by offline simulation.
- Real-time simulation (e.g. IAV KATsim)
- Impact of catalyst aging taken into consideration
- Algorithm development in ASCET or MATLAB
- Real-time validation of software changes
Urea metering system
As ammonia uniformity at the catalyst inlet is one of the key parameters determining SCR system performance, IAV’s vast portfolio also includes characterizing and developing the system. This includes systems for dosing liquids (e.g., AdBlue, Denoxium) as well as for dosing gases (e.g., AdAmmine).

- Determination of hydraulic dosing characteristics:
  - Linearity of dosing map
  - Influence of temperature
- Optical spray analysis under engine-like conditions:
  - Global spray parameters
  - Shot-to-shot stability
  - Droplet size & velocity distribution
  - Optical spray patternator
- Techniques applied:
  - Mie, Schlieren, LIF, LIEF, PIV
  - Long-distance microscopy
  - Laser diffraction spectrometry (LDS)
- Delivery of input data for CFD simulation
- Laboratory testing of alternative ammonia precursors

SCR mixing section
Ammonia distribution is extremely important in maximizing SCR efficiency, minimizing AdBlue consumption and reducing ammonia slip. To investigate the SCR mixing section, optical measurements are used for visualizing the droplet path in the fully assembled exhaust line.

- Laser-supported droplet distribution measurements
- Sampling upstream and downstream of the mixer
- Visualization of droplet / mixer interaction
- Sampling in across of the catalyst cross section
- Validation of simulation results
- Verification of different geometries

Catalysts – Synthetic-gas test bench (SCAT)
The catalysts are selected and characterized in the laboratory. In addition to high reproducibility, the independence of mass flow, concentration and temperature are a key advantage in development.

- Benchmarking of catalyst and DPF technologies
- Provision of characteristic catalyst data for simulation
- Basic calibration of ECU models
- Estimation of catalyst aging effects
- State-of-the-art gas analysis (CIMS, FTIR, NDIR etc.)
- Capability of testing full catalysts and small samples
- Capability of aging fully assembled aftertreatment systems (LD + HD) at low cost
The SCR Supply System is the origin of the whole NOx conversion. Some of the basic functions are storing, heating and filtrating of the urea. Furthermore it contains sensors for fluid level, temperature and quality. The reduction agent will be supplied to the injector and finally to the exhaust aftertreatment process with specific requirements.

Preliminary Development / Simulation

In an early stage of the development it is essential to understand the basic effects and behaviors of urea under different boundary conditions. It is necessary to focus on freezing and heating of the fluid. A very effective way to illustrate the multifaceted properties of freezing and heating and is to simulate the phase-changing. Transparent prototypes are essential for filling and venting tests, as well as for evaluating the sloshing behavior.

Component Testing

Based on the urea characteristics every component of the system has to fulfill specific requirements. For example:

- Heater
  - Regulation requirements, Working Day Cycle, calibration
- Supply module
  - Start up, operating performance, endurance testing
- Fill level detection
  - Height to volume diagram, calibration, inducement strategy
- Quality sensor
  - Sensitivity, OBD calibration and validation
- Reservoir
  - Freezing tests, sloshing, filling and venting
- Dosing line
  - Heating performance, temperature-resistant, freezing robustness

Vehicle Testing and calibration

Integration of the system into the vehicle includes the verification of all functions under extreme conditions and dynamics. Therefore vehicle testing in cold and warm regions and with low ambient pressure is part of the integration process.

A major focus of calibration is the behavior of the system around the AdBlue freezing point temperature and below. Level sensing and the subsequent inducement strategy are additional steps of the software development.

Due to quieter engines, there is more focus on the acoustic behavior of system components in operational mode and in the after-run, as well as sloshing noises of the fluid.

Readiness for start of production

Our experience in integration does not end with the handing over of a release recommendation. Support during series production, fast trouble shooting, task force work and benchmarking are parts of our business as well.
Package and Design

The SCR system is integrated into the vehicle in several development stages. In addition to designing the reductant tank or replacement cartridges, the exhaust system must also be adapted to the vehicle's boundary conditions and optimized in terms of best possible mixture preparation and minimum back-pressure.

Tank system and cartridge design
- Data preparation and space analysis
- Concept development giving consideration to the quantity of reductant required
- Concept assessment
- Detailed design in Catia V5 or ProE
- Generation and maintenance of technical drawings and bill of material
- Coordination of prototype and mass production

Mixing section and exhaust line design
- Layout of catalysts in terms of geometry and position
- Selection of sensors and injectors
- Generation of package concepts, including:
  - Catalyst, sensors, muffler
  - Mixing section (mixer and dosing point)
  - Routing of exhaust line
- Concept assessment supported by CFD investigations
- Extensive experience with various types of mixing elements
- Detailed design and technical drawings
- Coordination of prototype and mass production

CFD simulation
- Optimization of exhaust-system design from the aspect of fluid mechanics
  - General layout
  - Catalyst inlet funnel
  - Mixing devices
- Analysis of AdBlue injection
  - Spray penetration
  - Thermolysis/hydrolysis
  - Wall-film formation/heat transfer
  - Ammonia distribution at catalyst
- Minimization of spray-wall interaction
- Injection of gaseous ammonia
  - Layout and development of doser
Basic SCR system calibration takes place on the engine test bench after selecting the hardware and provides the starting point for further development in the vehicle. This is where the interaction between engine emission control, temperature management and SCR performance undergoes iterative optimization.

**Light-duty engine calibration**
- Engine combustion calibration (steady-state and transient)
- Engine calibration to achieve low fuel consumption & raw emissions
- SCR feed-gas calibration to enhance SCR efficiency
- Calibration strategies for SCR/DPF
- Engine warm-up strategies
- Comparison of engine and vehicle behavior
- Option for efficiency reasons: modeling derivative vehicle calibration at the engine test bench using VeloDyn
- Definition of engine operating-state strategy for GDI vehicles

**SCR calibration**
- Ammonia distribution measurements to confirm CFD results
- SCR calibration for emission cycles (e.g. NEDC, FTP, SC03, US06, JC08 etc.) and real-life behavior (e.g. ARTEMIS):
  - Calibration of fast SCR heat-up strategy
  - Ammonia dosing strategy and NOx conversion calibration
- Urea-decomposition validation
- Minimization of ammonia slip
- Calibration of adaptive SCR functions

**Heavy-duty applications**
- Reducing NOx on a lasting basis is extremely complex and costly
- SCR calibration for steady-state and transient test cycles (ESC, ETC, FTP, WHTC/WHSC & NRTC/NRSC)
- Full engine-map calibration taking into account Not-To-Exceed limits (NTE) and In-Use compliance
- Calibration of AdBlue/fuel consumption trade-off
- Calibration to achieve the lowest level of ammonia slip
- Robustness and endurance tests
- Emission certification on engine test bed
Algorithm Development and On-Board Diagnostics

Electronic algorithms are being developed for controlling and monitoring individual components. Robust calibration is crucial to the way in which the SCR system operates. The use of variable test environments allows virtually any hardware to be adapted and integrated in the overall system.

Software tools
- IAV – CalGuide
- IAV – CaliAV
- IAV – Themos, TR-Sim
- ATI – Vision, No-Hooks
- dSPACE – CalDesk, Controldesk
- ETAS – INCA/ASCET/Intecrio
- Imagine LMS® – AMESim
- MATLAB® – Simulink®, RT Workshop
- Vector – CANalyzer, CANoe, CANape
- Gamma Technologies – GT-Power
- HiL simulations: dSpace, IAV, customer

SCR control and diagnostics development
- Software development for diesel and gasoline engines
- SCR dosing strategy could be used from IAV or OEM/Tier 1
- Model-based development of control algorithms
- Algorithm design and calibration on target system
- Software and hardware integration
- Rapid prototyping hardware for concept applications
- Adaptation of dosing strategy to customer hardware

On-Board Diagnosis
- Development of OBD strategies
- SCR conversion and feed-gas monitoring
- Aftertreatment sensor monitoring: NOx, Lambda, PM
- Validation and certification of OBD concepts
- Robust calibration of diagnoses
Calibration Process

Once the system has been defined in full and undergone basic calibration, it is validated by IAV for mass production. A concept that is developed is only successful if it provides faultless performance under all operating conditions occurring in the real world at any time during the vehicle's lifespan. IAV possesses vast experience and can draw on established processes for developing and calibrating turnkey SCR systems for mass production.

Validation of output from r&d phase
- Supplier selection and management
- Demonstrator vehicle setup & technology validation
- Software, diagnosis and function analysis
- Validation and verification test plan
- FMEA analysis/risk management
- Quality gate compliance

Production phase
- Vehicle calibration
- Optimization of drivability, acoustics and NVH
- Robustness & durability testing (altitude, hot, cold)
- Minimization of urea deposit formation
- Driver inducement
- Emission test cycles (NEDC, FTP75, Artemis etc.)
- Optimization of trade-off between fuel and reductant (e.g. AdBlue) consumption
- Tool-guided dataset management (CalGuide®)
- Tool-chain-assisted calibration process and standards
- Full OBD calibration and validation
- Calibration and validation of tank thawing and heating strategy
- Homologation process and testing

Post-production phase
- Start-of-production support
- In-field compliance
- Failure analysis and task-force service
- Problem-solving teams

Vehicle calibration

Drive-cycle certification

Vehicle testing under all conditions