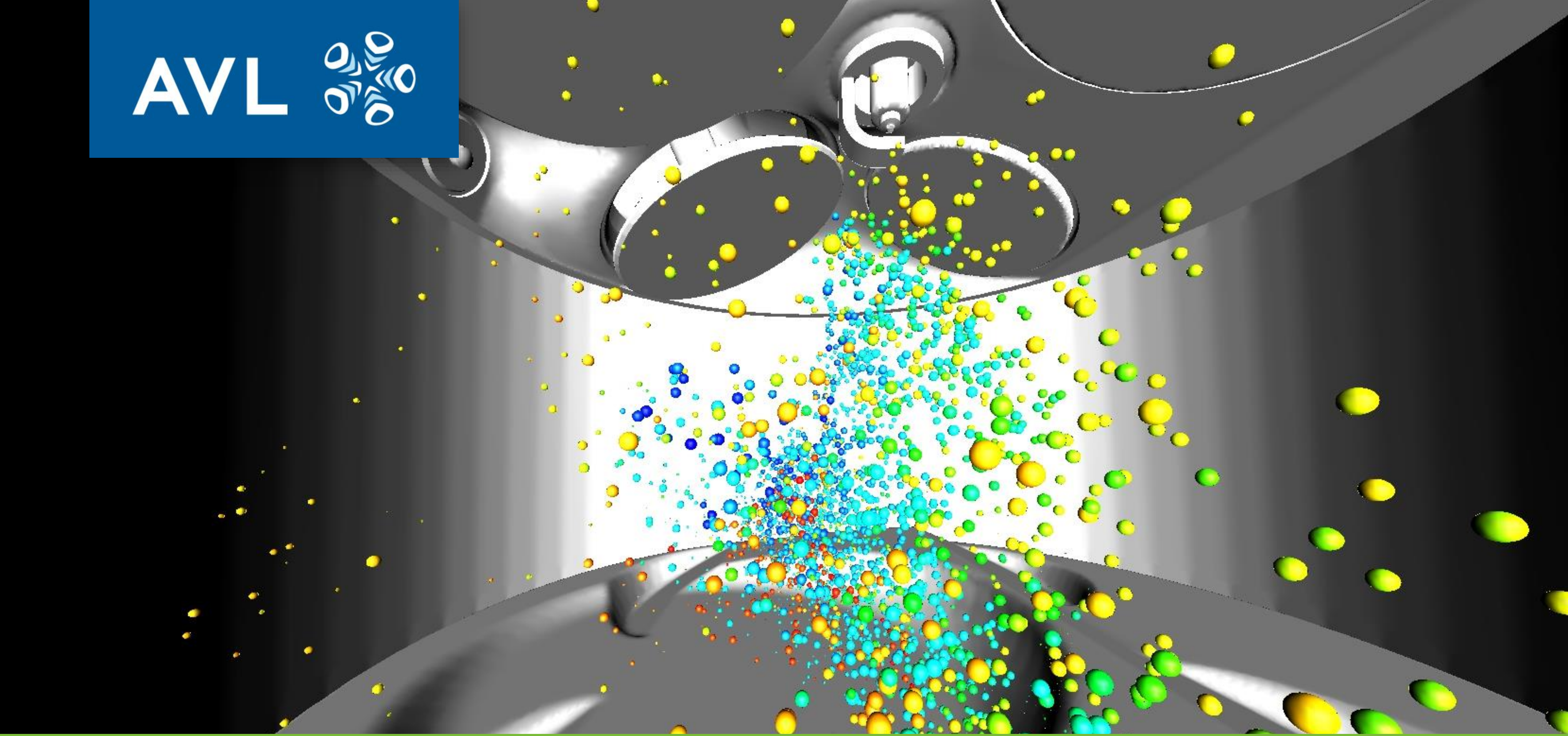


WHITE PAPER

Reducing GDI Engine Soot Emission by Minimizing Nozzle Tip Wetting

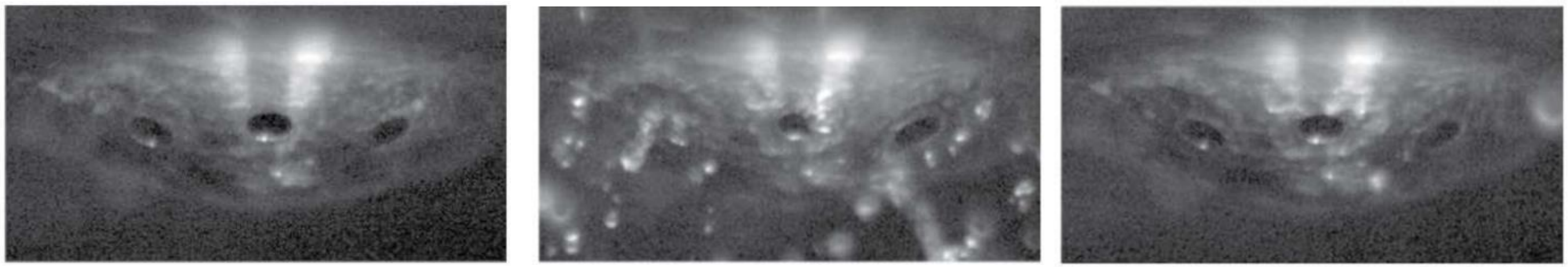
Executive Summary

When fuel is burned in an internal combustion engine (ICE), pollutants harmful for human health and environment are released . The current public discussion focuses on nitrogen oxides emitted by Diesel engines. Another hot topic for OEMs is to find ways to reduce particulate matters produced by gasoline direct injection (GDI) engines.

A large portion of the particles generated during a GDI engine's working cycle comes from "sooting diffusion flames", which appear at the tip of the injection nozzle. The target of today's development is to reduce tip wetting as its cause. Potential measures focus on the design of the injection nozzle and the combustion chamber. Additional influencing factors are engine operation and fuel composition.

With the help of simulation, development engineers can easily analyze given designs and conditions regarding wall wetting and the occurrence of diffusion flames. As a result, various possibilities to reduce tip wetting and to lower engine out raw emissions open up to them.

Injector tip



at start of injection

at the end of injection

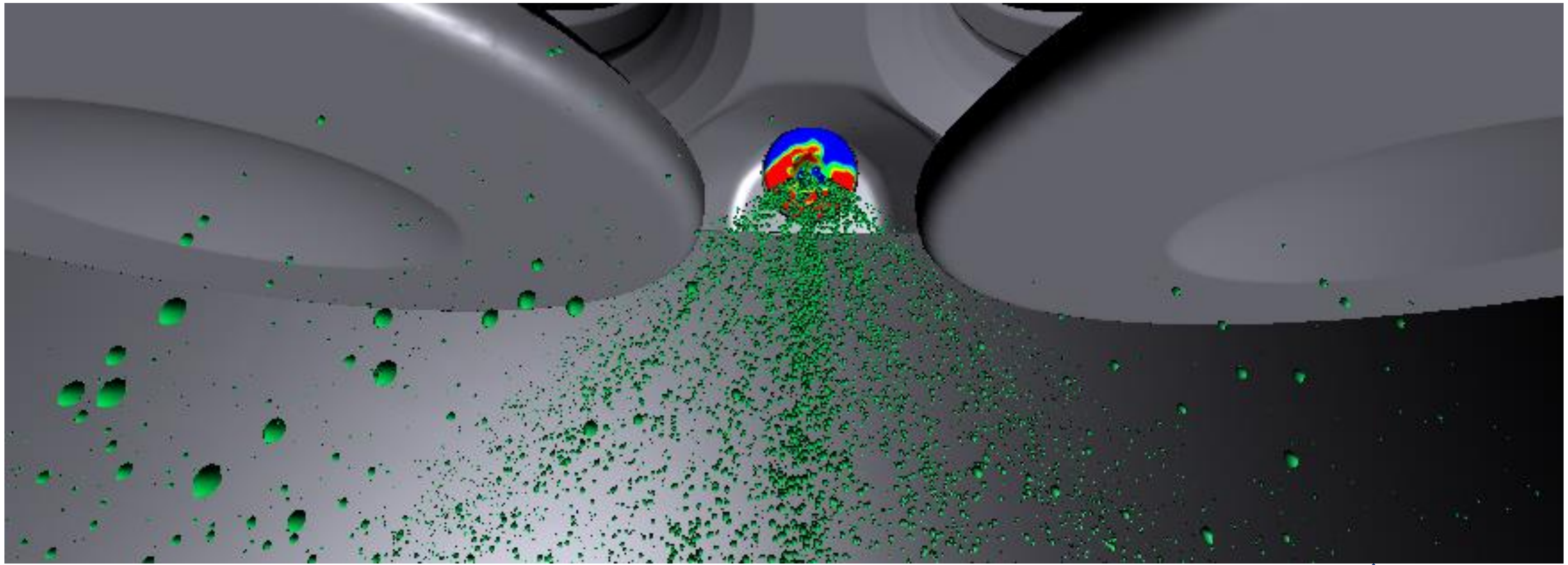
after injection, with fuel remaining attached

FEATURES

Introduction

After outlining the challenges faced in the development of GDI combustion engines, a simulation methodology will be presented, which detects nozzle tip wetting and determines its impact on soot formation.

To enable a simulation-driven development of a high-performance, low-emission combustion system, the deployed software has to meet a multitude of requirements. These will be explored in detail in this White Paper.



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The Challenge

In GDI engines, fuel is directly injected into the combustion chamber. This allows for higher power output, lower fuel consumption and consequently lower CO_2. It also offers better possibilities for emission control. However, GDI engines produce soot, with the root cause being wall film. This means that thin layers of fuel which are formed when injected droplets hit valves, liner or piston. Another factor is that fuel remains attached to the nozzle tip at the end of each injection event.

Unable to evaporate before the flame arrives, the film is combusted in a diffusion flame. This generates a large amount of soot particles. These are either emitted during the subsequent exhaust stroke or keep sticking to the system walls. Here, they build up a continuous, permanent soot layer.

The occurrence of wall film due to droplet impingement can be controlled relatively easy by choosing the right injection strategy and taking relevant design measures. Getting rid of nozzle tip wetting, however, proves more difficult. The formation of a soot layer at nozzle tip worsens the situation as the local mixing of fuel and air further slows down. This results in even higher particle numbers.

clean injector tip

coked injector tip

FEATURES

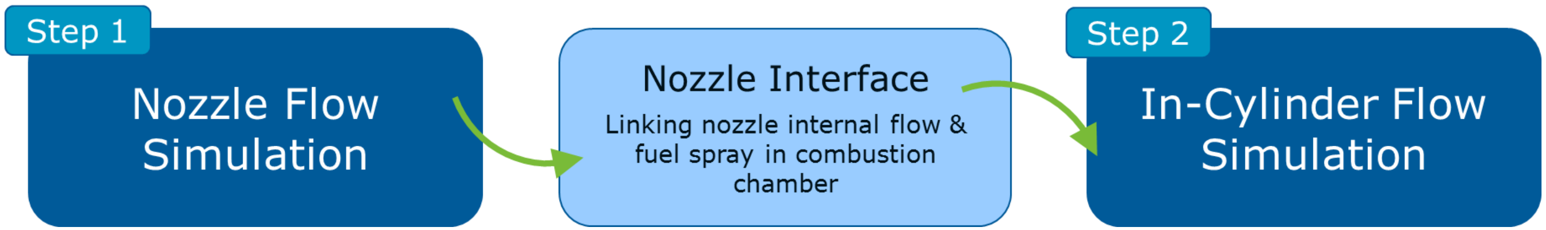
The AVL Solution

Nozzle tip wetting can be reduced significantly by analyzing virtual prototypes. To do so, geometrical representations of the real hardware, injection nozzle and combustion chamber have to be reflected accurately in simulation models. The impact of design modifications and operating conditions is being tested virtually. In the best case scenario, the first real prototype meets all performance requirements.

The ideal simulation software is expected to offer the following capabilities:

- Account for temperature and pressure dependent fuel properties impacting cavitation and flash boiling
- Link the internal flow in the injection nozzle with the fuel spray in the combustion chamber
- Offer detailed fuel spray and wall film models
- Handle pre-mixed and diffusion combustion simultaneously
- Provide reliable emission formation models
- Process a large number of simulation models fast

This simulation method implies two steps, which are connected through the “Nozzle interface”:

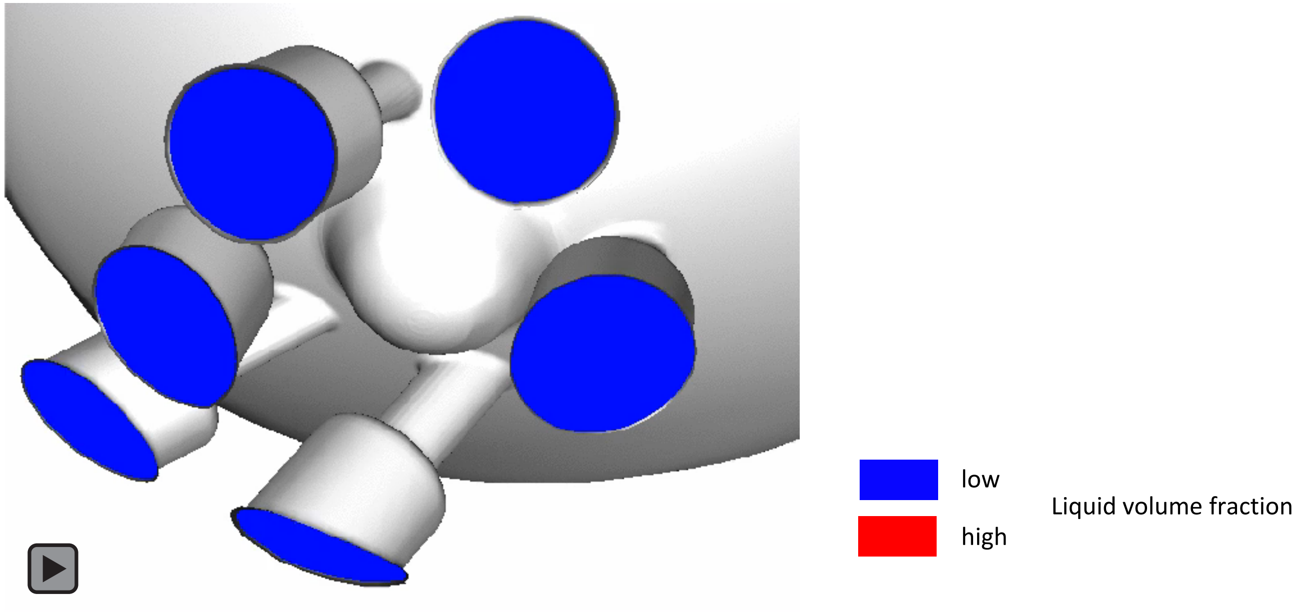


FEATURES

The AVL Solution

Nozzle flow simulation

In step 1 of AVL's simulation solution, the flow in the nozzle is computed. It is represented through three different phases: air, liquid gasoline and vaporized gasoline. Dedicated interface exchange models for are applied accounting also for cavitation. The computational model represents the tip of the nozzle body with the injection holes and the moving injection needle. The simulation covers the complete injection event including pre, main and post injections. Simulation results are phase, velocity and pressure distributions in the orifice exit areas, which are the interfaces between internal nozzle flow and combustion chamber spray.

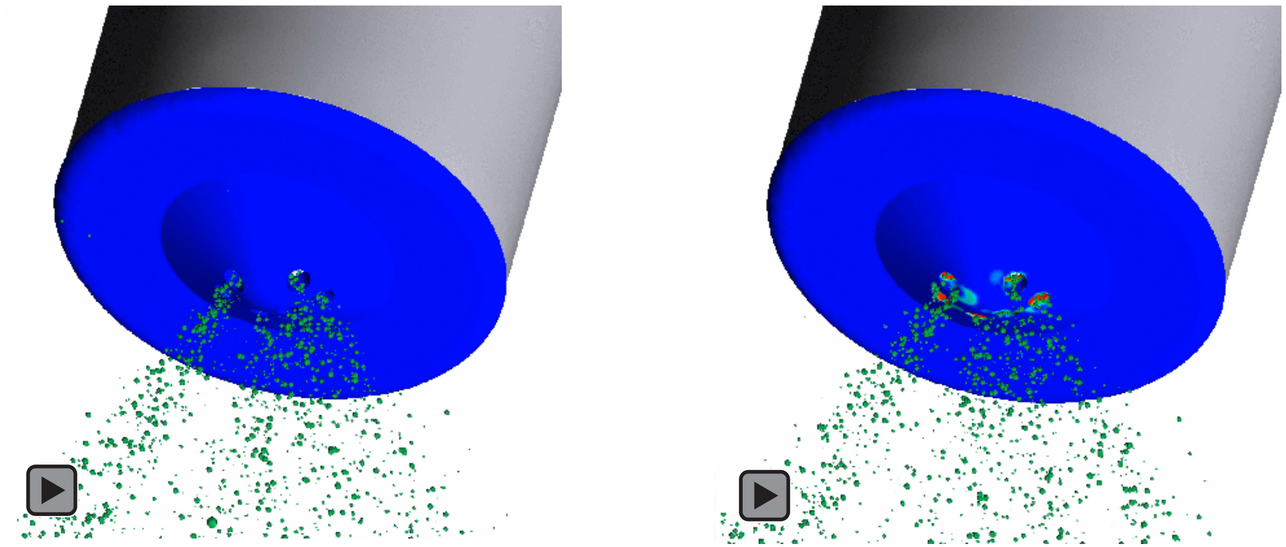


The AVL Solution

Nozzle interface

The AVL FIRE™ **Nozzle Interface** links the fuel flow inside the injection nozzle and the fuel spray in the combustion chamber.

Coupling Nozzle Flow and **In-Cylinder Flow** allows the initialization of the fuel spray simulating the fuel injection into the combustion chamber based on the time-varying flow conditions at the nozzle orifices. AVL FIRE™ is thus able to account for gradients in pressure, velocity and turbulence in the individual orifice areas impacting fuel discharge rates, spray angles and penetration and all related phenomena.



low
high
Fuel film height

Fuel attached to nozzle tip: nearly dry conditions on the left, wet conditions on the right

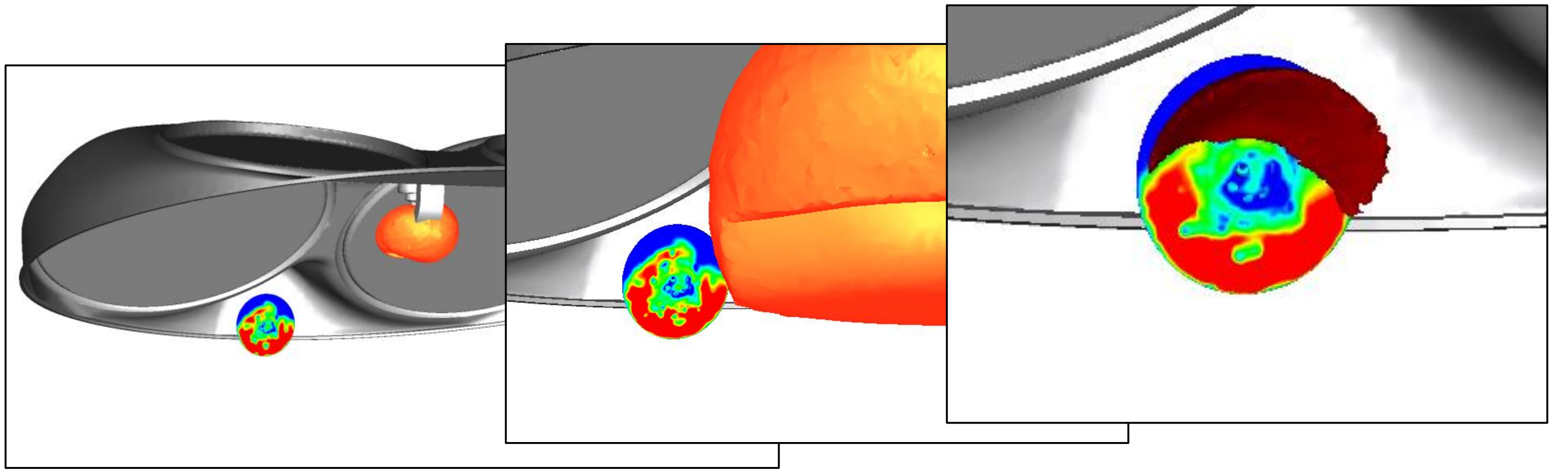
The AVL Solution

In-cylinder flow simulation

In step 2, the flow in the combustion chamber is calculated. During this step, AVL FIRE™ accesses the results of the nozzle flow simulation via the nozzle interface.

With the fuel velocity decreasing towards the end of each injection event, residual fuel remains sticking to the nozzle tip. Additional fuel droplets may be re-attached to it due to the interaction with the nearby in-cylinder flow.

The simulation allows to determine both, the amount of fuel attached to the nozzle tip which is evaporated before the arrival of the flame and, respectively, the amount which ends up in a diffusion combustion. In diffusion flames the flame speed is limited by the rate of diffusion at which fuel and oxidizer mix. In case of strong tip wetting, the amount of the available oxidizer is inadequate compared to what is needed for a complete combustion of the deposited fuel. This leads to a significant soot production.

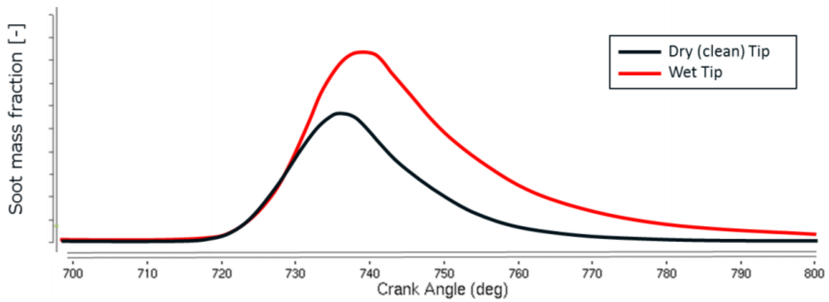


Ignition   Combustion   Sooting diffusion flame at nozzle tip

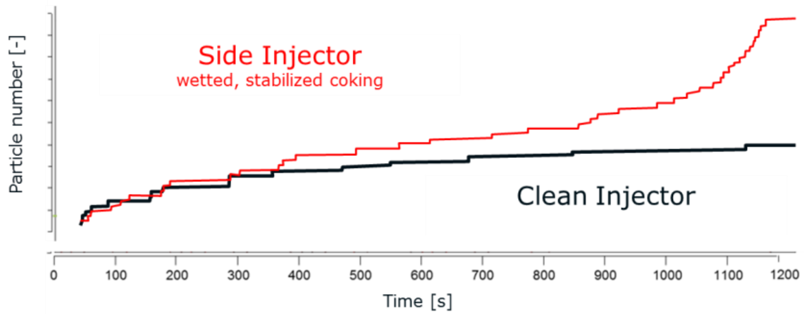
AVL

AVL Case Study

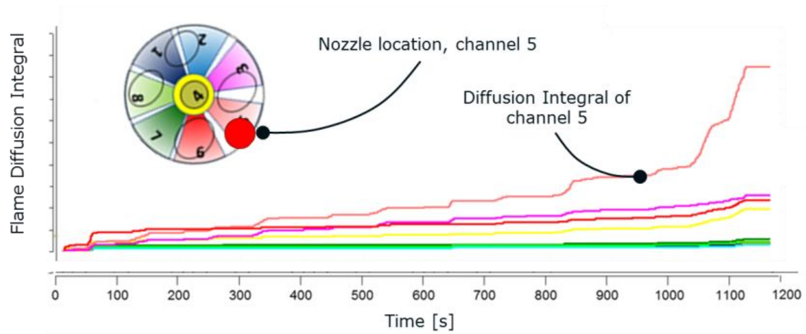
AVL applied this simulation solution to compare different designs resulting in different degrees of tip wetting. As the graphs show, the proposed simulation procedure predicts a higher amount of soot for the wet nozzle tip.



These results are confirmed by engine measurements. Particle numbers are significantly higher due to tip wetting leading to the formation of a thin coking layer.



AVL's VISIO Technology interprets light caught by optical fibers arranged in the engine's spark plug. Channel 5 detects "more light" as the sooting diffusion flame occurring at nozzle tip is much brighter compared to the pre-mixed combustion flame.



For details re. AVL's VISIO Technology, please refer to https://www.avl.com/visiolution

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Case Study ←

Conclusion

Conclusion

Making engines cleaner.

AVL FIRE™ is leading the way as *the* simulation solution for determining nozzle wetting and its impact on engine out soot. With the software's help, engineers can take design decisions confidently to effectively reduce tip wetting as major cause for soot generation in GDI Engines.

AVL has been working with a multitude of industry partners to prove the tool's unrivalled performance in practical applications.

AVL is the world's largest independent company for development, simulation and testing technology of powertrains (hybrid, combustion engines, transmission, electric drive, batteries and software) for passenger cars, trucks and large engines. Headquartered in Graz, the company has 45 affiliates worldwide and employs 9.500 employees worldwide whereof 3.850 are working in Graz. The company achieved a turnover of 1.55 Billion Euro in 2017.

The business organization of AVL List GmbH is divided into three units:

- Development of Powertrain Systems
- Engine Instrumentation and Test Systems
- Advanced Simulation Technologies

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