

# 3D-CFD In-Nozzle Flow Simulation and Separate Row Injection Rate Measurement as preparatory steps for a detailed Analysis of Multi-Layer Nozzles

C. Menne<sup>1\*</sup>, A. Janssen<sup>1</sup>, M. Lamping<sup>2</sup>, T. Körfer<sup>2</sup>, H.-J. Laumen<sup>2</sup>, M. Douch<sup>2</sup>, R. Meisenberg<sup>2</sup>

<sup>1</sup>Institute for Combustion Engines  
RWTH Aachen University, Germany

<sup>2</sup>FEV Motorentchnik  
Aachen, Germany

Multilayer nozzles for diesel engines with parallel or convergent nozzle hole arrangement and small nozzle hole diameters offer the potential to combine good mixture preparation with high spray penetration and air utilization at medium and higher load engine operating points. Advanced experimental injection rate measurement and 3D CFD in-nozzle flow simulation allow the determination of the detailed boundary conditions at the nozzle outlet for layer I and II of the nozzle and show that also for equally sized holes especially during the phase of needle opening different injection rates occur for upper and lower row.

## Introduction

Modern Diesel engines have to comply with very stringent emission standards and, in parallel have to achieve market acceptance with excellent performance and fuel consumption. Besides the combustion system itself and the air path including turbocharging, the Fuel Injection System (FIE) is in the center of development focus. In the past, high injection pressure levels with more than 1600 bar and multi-injection capability in conjunction with highly accurate and reproducible injection quantities have been enablers for the wide acceptance of direct injection diesel engines and the achievement of EURO-4 and -5 without DeNOx aftertreatment. In order to maintain the efficiency benefit of Diesel engines also in comparison to modern turbocharged direct injection gasoline engines and to comply with future CO<sub>2</sub> and emission legislation further development in the field of injection equipment is necessary. One proposal is to further reduce spray hole diameter to improve mixture preparation. Fig. 1 shows the general development of spray hole number and nozzle orifice diameters versus time.

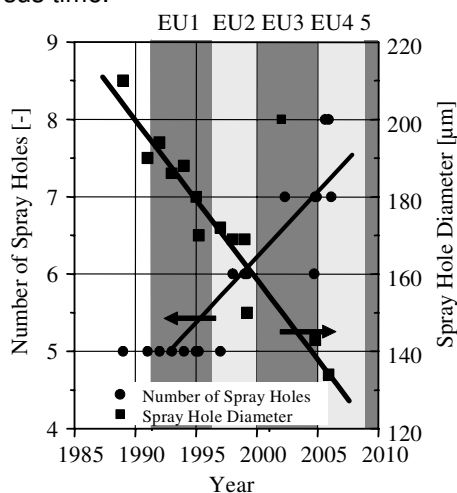


Fig. 1: Evolution of Spray hole number and spray hole diameter

The effects of smaller spray holes with increased efficiency have been discussed in detail in the past. Smaller spray holes result in reduced droplet diameters and, subsequently, in an increased air entrainment into the fuel sprays and enhanced mixture formation [2]. Therefore, the implementation of smaller spray holes typically results in an improved NO<sub>x</sub>-PM tradeoff at part load operation, whereas the hydraulic flow rate is reduced due to the diameter reduction which typically affects the full load performance negatively [1].

Consequently, the idea arises, to combine small spray hole diameters with a sufficient hydraulic flow, which leads to a significant increase of spray hole numbers. But not only overall hydraulic flow rate is important. If the impulse of a single separate spray is not sufficient to penetrate the complete piston bowl under high load in-cylinder conditions, poor air utilization and subsequent soot emissions can be a consequence. One approach to combine good mixture formation due to small nozzle hole diameters with adequate spray impulse is to use multi layer nozzles with nozzle holes arranged in groups. In the course of a public financed research program the potential of grouped multi layer nozzles shall be analyzed with the help of fundamental spray investigations in high pressure vessels and detailed 3D CFD spray simulations. As a first step to gain a detailed understanding of the underlying mechanisms of multi-layer nozzles, the injection rate was determined separately for layer I and II of the nozzle. These investigations were accompanied by 3D CFD in nozzle flow simulations to understand the observed effects. Optical Schlieren investigations were used to validate in nozzle flow simulations and injection rate measurements.

## Investigated Nozzle Layout

Within the overall research project numerous multi layer nozzles with grouped nozzle holes were

\* Corresponding author: menne@vka.rwth-aachen.de  
Towards Clean Diesel Engines, TCDE2009

investigated. The chosen approach for layer assigned injection rate measurement and accompanying in nozzle flow simulation and optical validation shall be presented at the example of a multi layer nozzle with parallel nozzle holes. The main parameters of the investigated nozzle are shown in Table 1.

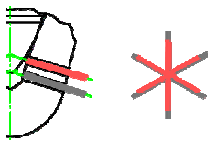
Hole Number "upper Row" [°]	Cone Angle "upper Row" [°]	HFR "upper Row" [cm³/30s @100 bar]	Twist Angle [°]	k-Factor [-]	Overall HFR [cm³/30s @100 bar]
3	153	185	0	1.5	370
Hole Number "lower Row" [°]	Cone Angle "lower Row" [°]	HFR "lower Row" [cm³/30s @100 bar]			
3	153	185			

Table 1: Geometric data and layout of the investigated nozzle ADD NOZZLE INLET VCO MICRO SAC

### Injection Rate Measurement

The realized injection rate is one of the key input parameters for spray and overall combustion simulation. For the investigated multi layer nozzles, where the nozzle holes are arranged on an upper and a lower row, the overall injection rate is not sufficient to describe the nozzle behavior as it cannot be assumed that the injection rate is comparable for holes of the upper and lower row. Especially for nozzle concepts with varying hole diameters for upper and lower row and during the needle opening phase a significant difference in injection rate can be expected. In order to analyze the impact of multi layer nozzle concepts on spray propagation, mixture preparation and finally combustion and emission formation it is necessary to measure and analyze these differences in injection rates.

In order to minimize the necessary machining effort and possible impact of any machining on the nozzle behavior, a high precision measurement tool was developed, adapted to the different nozzle geometries and calibrated. The nozzles are prepared with a 0.2 mm wide groove, which is machined on the entire circumference of the nozzle tip. The groove is located between the upper and lower nozzle layer and is a defined surface for sealing which also ensures that the injector is centered in the layer separator tool. Figure 2 shows the developed injection rate measurement tool.

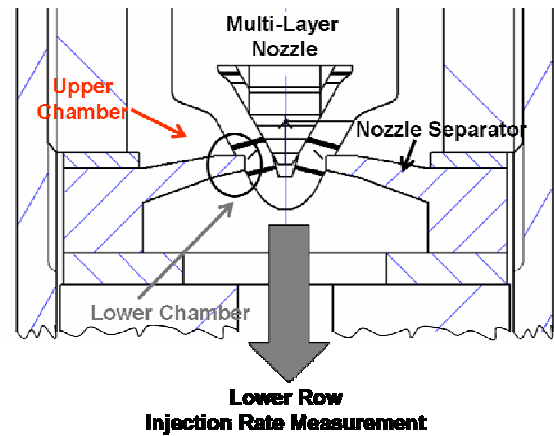


Fig. 2: Tool for separate layer injection rate measurement

The lower chamber of the injection rate measurement tool is connected to an injection rate analyzer with high resolution data logging capabilities and a precise fuel mass measurement. A comparison of injected fuel mass via upper and lower nozzle layer is shown in Fig.3.

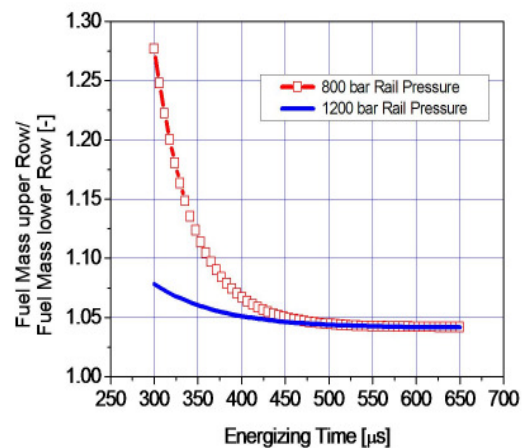


Fig. 3: Ratio of Fuel Mass injected via upper and lower nozzle row

The separate injection quantity measurements for the upper and lower layer show that especially for low rail pressure levels, e.g. 800 bar and injection durations with energizing times less than 400 micro seconds the fuel quantity that is injected via the upper row is up to 25% higher in comparison to the fuel quantity that leaves the lower layer. A measured injection rate profile for a typical pilot injection as shown in Fig. 4 with an energizing time of 300 micro seconds and a rail pressure of 800 bar confirms the results of the fuel mass measurements.

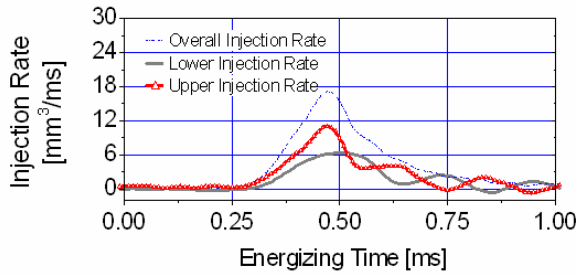


Fig. 4: Injection Rate for upper and lower layer (800 bar; 300micro seconds energizing time)

### 3D – CFD In Nozzle Flow Simulation

In order to better understand the experimental results a 3D CFD simulation model was created with StarCD.

To reduce calculation time and meshing effort a sector mesh for one pair of nozzle holes was set up. Fig. 5 shows the realized mesh.

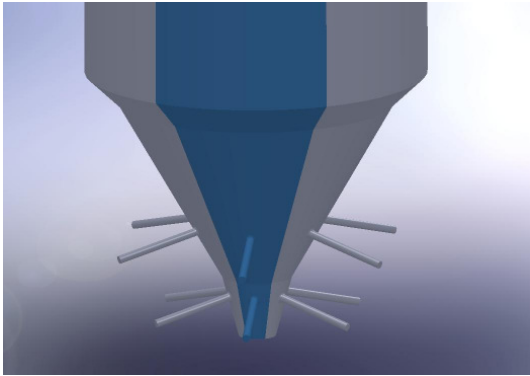


Fig. 5: Sector mesh for 3D CFD Simulation Model

Steady state flow calculations were carried out for three different needle lift positions:

- 1) almost closed / slightly open
- 2) mid-open position
- 3) completely open

As especially for low rail pressures and short energizing times, differences in injection rate and subsequent injected fuel mass could be identified for upper and lower row, high emphasis was put on simulations with a mesh corresponding to needle lift position 1). Figures 6 and 7 show the obtained velocity vectors for the simulated flow fields in the area of the upper and lower orifice. The low needle lift and subsequently reduced cross section, available for the flow from the upper part of the injector to the lower orifice in the micro sac area has a significant throttling effect. In spite of the significantly improved conditions for the flow at the immediate orifice inlet in the micro sac and the worse conditions at the valve-covered-orifice (VCO) in the

upper row, the throttling results in a higher injected fuel mass via the upper orifice under these boundary conditions.

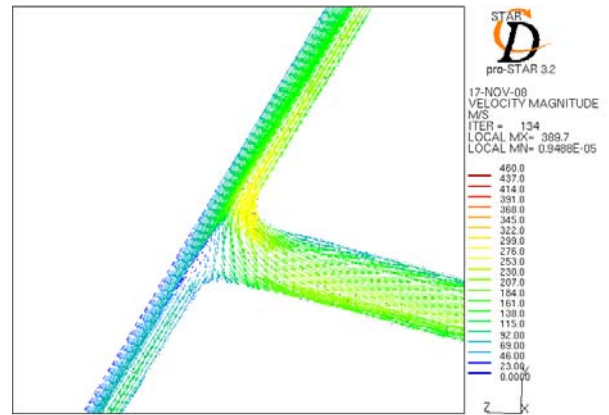


Fig. 6: Velocity Vectors for almost closed needle position in upper orifice (VCO-type), (800 bar Rail Pressure)

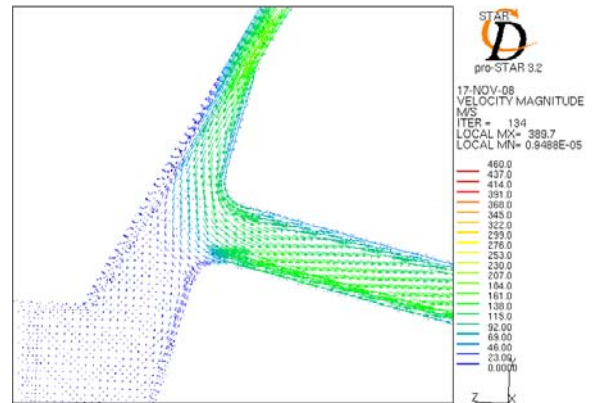


Fig. 7: Velocity Vectors for almost closed needle position in lower orifice (Micro-Sac-type), (800 bar Rail Pressure)

### References

- [1] M. Lamping, T. Körfer, H.-J. Laumen, H. Rohs, S. Pischinger, H. Neises, H. Busch Einfluss des hydraulischen Düsendurchflusses auf das motorische Verhalten bei Pkw-DI-Dieselmotoren 8. Tagung Motorische Verbrennung, 2008
- [2] Y. Matsumoto, J. Gao, M. Namba, K. Nishida Mixture Formation and Combustion Processes of Multi-Hole Nozzle with Micro Orifices for D.I. Diesel Engines SAE Paper 2007-01-4050