INTRODUCTION

The quality of liquid atomization is probably the most essential factor for reducing emissions in Diesel engines. The atomization process depends among other things on the velocity of the fuel exiting the injection nozzle and on the extent of cavitation within the nozzle. Exit velocity modulations strongly influence the break-up processes, the spray penetration and also the inter-droplet and wall-droplet interactions.

The problem of fuel injection has always been in centre of new technological developments. The technical and economical requirements include reduction of the concentration of pollutants in emission and economical consumption as well as optimal reliability and performance. A great progress in this area has been obtained with the introduction of the Common-Rail-Systems and pump-injectors in past two decades. Both methods use the advantages of high injection pressures.

One of the essential aspects of this type of injector is the occurrence of cavitation in each injection hole due to the fall of the static pressure at the holes entrance. The cavitation process within the nozzles may play a major role in the spray break-up [1-4].

In addition to further progress in the development of efficient and conventional injection methods, the atomization must be improved as well as the power consumption. Herewith a spray can play a leading role in improvement and refinement of injection strategies.

One possible approach to solve this problem is to use of Laval or coaxial nozzles. The atomization process in such nozzles occurs by fragmentation between high velocity gas jet and fuel volume.

Coaxial nozzles are effectively used in Rocket Engines [5]. In this case the interaction between the high velocity of gas (fuel) and the low velocity of liquid (oxygen) occurs.

A similar process of atomization in liquid/gas systems is observed in Laval nozzle. The Laval nozzles are employed in textile industry for generation of nonwovens (so-called Nanoval process) [7]. In this case the melt flow leaves the spinneret and seized by adjacent gas, which is accelerated according to gas dynamics rules in Laval nozzle. The gas flow may reach a sonic or even supersonic speed. At the same time the melt flow is splitting into a multitude of fine filaments about 1µm diameter in size.

In both coaxial and Laval nozzle the atomization might be reached by low volume flux of liquid. Therefore it is interesting to study an atomization process for liquid/gas systems when liquid is a fuel (in our case Diesel). A dispersion of particles will be employed as the control parameter for determination the quality of the injection.

NUMERICAL METHOD

The calculations have been performed using the CFD codes of STAR-CD with the second-order differencing schemes MARS (monotone advection and reconstruction scheme) and CD (for density only). For the nozzle air flow simulations the supply pressure and chamber pressure were prescribed at the in- and outlet, respectively. The simulations were carried out considering turbulent flows. The Reynolds-averaged Navier-Stokes equations were solved together with the k-ε RNG model. For the spray computations, the break-up model of Hsiang and Faeth [8], collisions model of O’Rourke [9], wall-interaction model of Bai and Gosman [10] and
atomization model of Chaves and Obermeier [11-12] have been used.

The Hsiang and Faeth model covers all types of break-up that are of interest in Diesel engine spray applications. The characteristic break-up time is

$$\tau = \frac{5}{1-(Oh/7)} \frac{D_d}{\bar{u} - \bar{u}_d} \sqrt{\frac{\rho_d}{\rho}},$$  \hspace{1cm} (1)

where $D_d$ is the instantaneous droplet diameter, $\bar{u}_d$ – the droplet velocity and $\rho_d$ is droplet density. $Oh$ – the Ohnesorge number

$$Oh = \frac{\mu_d}{(\rho_d D_d \sigma_d)^{1/2}},$$ \hspace{1cm} (2)

where $\sigma_d$ is surface tension and $\mu_d$ is droplet viscosity.

The estimated stable droplet diameter is given by the equation

$$D_s = 6.2 D_d \left( \frac{\rho_d}{\rho} \right)^{1/4} \sqrt{\frac{\mu_d}{\rho_d D_d (\bar{u} - \bar{u}_d)}}.$$

Break-up takes place when the drop Weber number is greater the critical value of

$$We_c = \frac{\rho (\bar{u} - \bar{u}_d) D_d}{2 \sigma_d} > 6$$ \hspace{1cm} (4)

The droplet diameters change according to following rate equation

$$\frac{dD_d}{dt} = \frac{D_d - D_s}{\tau}.$$ \hspace{1cm} (5)

The collision model of O’Rourke distinguishes between coalescence, separation and bouncing interactions.

As boundary conditions the atomization model proposed by Chaves and Obermeier [11] has been used. In the model, the liquid core is represented by a chain of primary droplets which leave the nozzle with the chamber velocity $u_{ch}$ and initial diameter equal to the nozzle diameter $D$. Secondary droplets are stripped off from the primary ones over the length of the liquid core $L_c$. The model assumes that the following two mechanisms are responsible for spray formation:

- Detachment of drops from the liquid jet core emerging from the nozzle by aerodynamic forces; the sizes of the drops produced depend on the position along the liquid core where stripping occurs and on the ejection angle, whose maximum value must be prescribed.
- Collision between the primary drops in the liquid core caused by the time varying injection velocity.

The time dependent process of atomization has been examined for 3 types of air/fluid nozzles. The corresponding CFD models for Laval, Converging and Coaxial nozzles with boundary conditions are presented in Fig. 1-3.

The calculations have been carried out for two variants of mass flow rate $8\times10^{-4}$ kg/s and $8\times10^{-5}$ kg/s and for pressure ratio of air $P_1/P_2 = 1.5; 2; 3; 4; \text{ and } 6$. For the converging and coaxial nozzles only one pressure ratio $P_1/P_2 = 2$ has been used. The aim of investigations is to observe the flows with small quantity and very low initial velocity of the liquid phase. The employed parameters are summarized in Table 1.
**Table 1. Numerical conditions**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle type</td>
<td>Laval, Converging, Coaxial</td>
</tr>
<tr>
<td>Hole diameter</td>
<td>0.2 mm</td>
</tr>
<tr>
<td>Air pressure ratio $P_1/P_2$</td>
<td>1.5; 2; 3; 4; 6</td>
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<tr>
<td>Fuel</td>
<td>Heptan</td>
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<tr>
<td>Fuel mass flow</td>
<td>8.e-5; 8.e-4 kg/s</td>
</tr>
<tr>
<td>Atomization model</td>
<td>Chaves and Obermeier (MPI-2) [11-12]</td>
</tr>
<tr>
<td>Break-up model</td>
<td>Hsiang and Fateh [8]</td>
</tr>
<tr>
<td>Collision Model</td>
<td>O’Rourke [9]</td>
</tr>
</tbody>
</table>

**NUMERICAL RESULTS**

The spray formations have been calculated transient with constant boundary conditions. The result analysis was performed at the time when spray characteristics have to reach a developed state (approximately 0.02 s).

At first the results for Laval nozzle are presented. A high quality atomization occurs even behind Laval cross-section. In Fig. 4 the proportional droplet distribution for fuel flow rate 8.e-4 kg/s and $P_1/P_2$=4 is shown. In this case a very strong atomization of fluid occurs and the droplets are almost invisible in the cylinder chamber because of their small size.

For the same case another picture in Fig. 5 is shown. Here all droplets are plotted with the equal size. The colours correspond to the diameter of droplets. The droplet size in the cylinder chamber is changing between 6 and 0.6 $\mu$m.

![Fig. 4. Spray formation in Laval nozzle by $P_1/P_2$=4 and $\dot{m}_{\text{Fluid}}$ = 8.e-4 kg/s. The droplet size [m] is proportionally presented.](image)

![Fig. 5. The same distribution as in Fig.4 with fixed plotted size of droplets [m].](image)

According gas velocities and Mach number for this case are presented in Figs. 6 and 7.

![Fig. 6. The Gas velocity [m/s] distribution for $P_1/P_2$=4 and $\dot{m}_{\text{Fluid}}$ = 8.e-4 kg/s.](image)

![Fig. 7. Mach number distribution for $P_1/P_2$=4 and $\dot{m}_{\text{Fluid}}$ = 8.e-4 kg/s.](image)

The extreme value of gas velocities and high Mach numbers play a significant role for the spray formation. On the one hand the fluid particles are accelerated due to the high...
gas velocity. On the other hand in the gas flow behind the nozzle the fluid particles tend to collapse which improves the process of atomization.

The quality of atomization has been studied analysing the mean droplet size $D_{50}$ in the chamber. This parameter can be determined by integrating the droplet size distribution. In Fig. 8 the resulting distributions for Heptan mass flow rate of $8.\text{e}-5$ kg/s are presented. It is shown, that higher pressure ratios $P_1/P_2$ lead to a finer atomization process. Furthermore, the difference between the cases $P_1/P_2 = 3$ and $P_1/P_2 = 4$ is small.

![Fig. 8. Integrated particle size distribution for $\dot{m}_{\text{Fluid}} = 8.\text{e}-5$ kg/s](image)

It was expected, that for higher mass flux and higher initial velocity of liquid the atomization will be yet finer. But the results presented in Fig.9 reflect, that the particles size for $\dot{m}_{\text{Fluid}} = 8.\text{e}-4$ kg/s is coarser than for $\dot{m}_{\text{Fluid}} = 8.\text{e}-5$ kg/s. Additionally, a more intensive evaporation takes place for higher mass flow rates.

![Fig. 9. Integrated particle size distribution for $\dot{m}_{\text{Fluid}} = 8.\text{e}-4$ kg/s](image)

A comparison of results obtained for two different mass flows in the Laval nozzle can be presented as dependence between mean particles size $d_{50}$ and gas pressure ratio. The results presented in Fig. 10 reflect that considerably particles size changes occur in domain of $P_1/P_2 = 2 \div 4$ for $\dot{m}_{\text{Fluid}} = 8.\text{e}-5$ kg/s. For a further increase of $P_1/P_2$ the atomization will be insignificantly changed. For obtain a similar atomization for higher fluid mass flow a higher air pressure ratio is needed.

![Fig. 10. Dependence between mean particles diameter and air pressure ratio.](image)

From Fig. 10 we conclude that for a fix pressure ratio better atomization is obtained for lower mass flow rate.

In Fig. 11 the change of $d_{50}$ in dependence from mass flow ratio $\dot{m}_{\text{Gas}} / \dot{m}_{\text{Fluid}}$ for Laval nozzle is presented. Fig. 10 and Fig. 11 reflect the phenomena that the possibility of even finer atomization for $\dot{m}_{\text{Fluid}} = 8.\text{e}-5$ kg/s is almost exhausted for the case $P_1/P_2 = 4$. The results reflect that atomization improves with smaller mass flow rates.

![Fig. 11. Dependence between mean particles diameter and mass flow ratio $\dot{m}_{\text{Gas}} / \dot{m}_{\text{Fluid}}$.](image)

The calculation of a spray formation for the converging nozzle reflects a similar effect as for the Laval nozzle. Namely finer droplets size has been observed for smaller $\dot{m}_{\text{Fluid}}$ for the same ratio of $P_1/P_2$. A direct comparison of the particle sizes obtained in the Laval and the converging nozzle is shown in Fig. 12. The corresponding probability density distributions for these cases are presented in Fig. 13.

![Fig. 12. Particles size distribution behind Laval and converging nozzle by $\dot{m}_{\text{Fluid}} = 8.\text{e}-5$ kg/s and $P_1/P_2 = 2$.](image)
Fig. 13. Probability density distribution behind Laval and converging nozzle by $\dot{m}_{\text{Fluid}}=8.\times10^{-5}$ kg/s and $P_1/P_2=2$.

Despite of similar shapes of the nozzles geometries the obtained results are different. It is shown that the diverging part of the Laval nozzle in combination with its converging part plays an important role. In this region very strong atomization of fluid occurs. In Figs 14 and 15 the gas velocity behaviour and spray formations in both nozzles are shown. For the case of the Laval nozzle the break-up of droplets is more pronounced than as for the converging nozzle.

Fig. 14. Laval nozzle: Distribution of gas velocity [m/s] and spray formation for $\dot{m}_{\text{Fluid}}=8.\times10^{-5}$ kg/s and $P_1/P_2=2$.

Fig. 15. Converging nozzle: Distribution of gas velocity [m/s] and spray formation for $\dot{m}_{\text{Fluid}}=8.\times10^{-5}$ kg/s and $P_1/P_2=2$.

Behind the simplified co-axial nozzle the qualitatively different droplets behaviour has been observed. The gas flow also improved the spray formation process, but we can see in Fig. 16 that the value of $\dot{m}_{\text{Fluid}}=8.\times10^{-5}$ kg/s is too small for this simplified geometry. The velocity distribution with spray formation for the case of $\dot{m}_{\text{Fluid}}=8.\times10^{-4}$ kg/s in Fig. 17 is presented.

Fig. 16. Coaxial nozzle: Distribution of gas velocity [m/s] and spray formation for $\dot{m}_{\text{Fluid}}=8.\times10^{-5}$ kg/s and $P_1/P_2=2$.

Fig. 17. Coaxial nozzle: Distribution of gas velocity [m/s] and spray formation for $\dot{m}_{\text{Fluid}}=8.\times10^{-4}$ kg/s and $P_1/P_2=2$.

Additionally the flow simulations with $\dot{m}_{\text{Fluid}}=3.\times10^{-4}$ kg/s have been performed. The results of these simulations confirm the observation obtained in Fig. 10 except for lowest mass flow rate in this simplified geometry (see Fig. 18).
Fig.18. Particles size distribution behind coaxial nozzle.

CONCLUSIONS

The presented numerical approach which includes the simulation of a compressible flow and spray formation makes possible to predict the grade of atomization behind air/fluid nozzles. It was found that for the considered nozzles the finer atomization occurs for slow initial velocities of fuel, i.e. for higher values of $\dot{m}_{\text{Gas}} / \dot{m}_{\text{Fluid}}$. Further, it was shown, that a higher gas pressure ratio $P_1/P_2$ improves the whole atomization process.

With the presented approach qualitative characteristics of nozzle flow and spray structures have been accurately predicted. The results are restricted to the selected nozzles geometries and the considered analysis of particles dispersion. It must be noted that effects like evaporation and penetration length are not considered in this paper.

ACKNOWLEDGMENT

The authors would like to thanks Dr. L. Gerking for interesting ideas and discussions.

NOMENCLATURE

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<tr>
<th>Symbol</th>
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<th>SI Unit</th>
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<td>Supply pressure</td>
<td>Pa</td>
</tr>
<tr>
<td>$P_2$</td>
<td>Chamber pressure</td>
<td>Pa</td>
</tr>
<tr>
<td>$\dot{m}$</td>
<td>Mass flow</td>
<td>kg/s</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Characteristic break-up time</td>
<td>s</td>
</tr>
<tr>
<td>$u$</td>
<td>Velocity</td>
<td>m/s</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density</td>
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<tr>
<td>$\mu$</td>
<td>Viscosity</td>
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<tr>
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REFERENCES