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NUMERICAL INVESTIGATION OF SPRAY FORMATION IN COAXIAL NOZZLES

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ABSTRACT
In this paper the results of numerical investigation of atomization process of liquid fuel (Diesel) in Laval and coaxial nozzles are presented. The calculations have been performed using CFD codes of STAR-CD. The dependences between the different cases of pressure drop and spray formation have been analysed. For that purpose a model to simulate unsteady two-phase atomization process has been employed. Results of transient flow through various 3D nozzle shapes and the resulting spray development have to be discussed. The three type of nozzle (Laval, converging and coaxial) are considered. It was found that for the nozzles under consideration the finer atomization occurs for low initial mass flow rates. The atomization process in such nozzles occurs by fragmentation between high velocity gas jet and fuel volume. Further, the pressure conditions of gas flow are of great relevance for atomization process.

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

$$\tau = \frac{5}{1-(Oh/7)} \frac{D_d}{|\vec{u}-\vec{u}_d|} \sqrt{\frac{\rho_d}{\rho}} , \qquad (1)$$

where D_d is the instantaneous droplet diameter, u_d – the droplet velocity and ρ_d is droplet density Oh – the Ohnesorge number

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

where σ_d is surface tension and μ_d is droplet viscosity.
The subscript d denotes the droplet/dispersed phase, non-subscripted quantities are taken to refer to the continuous phase.

The estimated stable droplet diameter is given by the equation

$$D_s = 6.2 D_d \left(\frac{\rho_d}{\rho}\right)^{1/4} \sqrt{\frac{\mu_d}{\rho_d D_d |\vec{u}-\vec{u}_d|}} . \qquad (3)$$

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

$$We = \frac{\rho |\vec{u}-\vec{u}_d|^2 D_d}{2\sigma_d} > 6 \qquad (4)$$

The droplet diameters change according to following rate equation

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

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 liquid nozzle hole is 0.2 mm in diameter for all nozzle types. Further the Laval and converging nozzles have an equal contraction diameter of 4 mm.

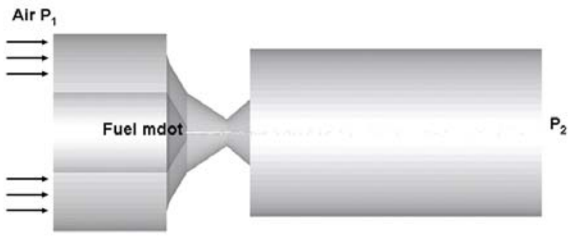

Fig. 1. Scetch of the Laval nozzle.

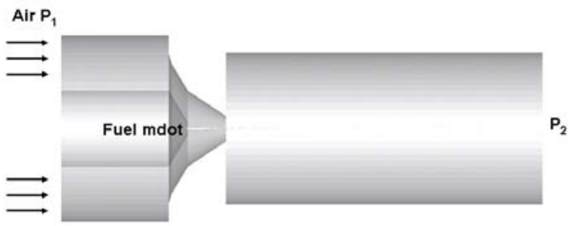

Fig.2. Scetch of the converging nozzle

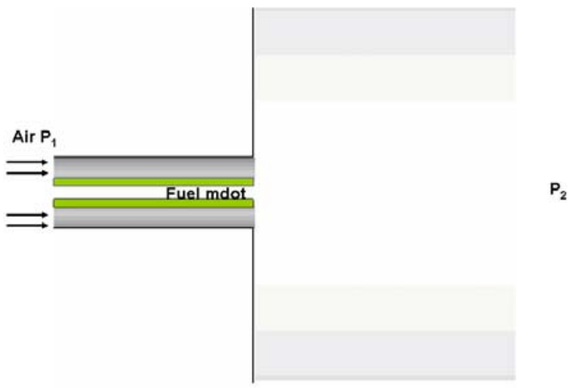

Fig. 3. Scetch of the coaxial nozzle

The calculations have been carried out for two variants of mass flow rate 8e-4 kg/s and 8e-5 kg/s and for pressure ratio of air P_1/P_2 = 1.5; 2; 3; 4; 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.

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

Table 1. Numerical conditions

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 µm.

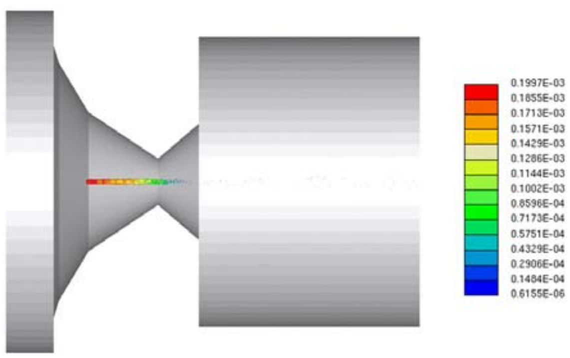

Fig. 4. Spay formation in Laval nozzle by P_1/P_2=4 and $\dot{m}_{Fluid}$ = 8.e-4 kg/s. The droplet size [m] is proportionally presented.

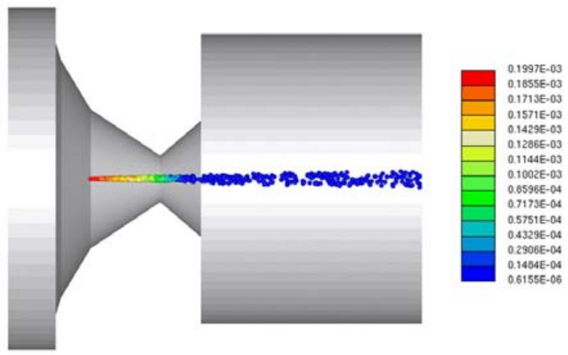

Fig. 5. The same distribution as in Fig.4 with fixed plotted size of droplets [m].

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

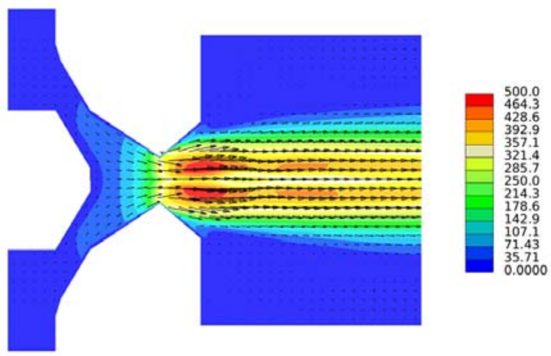

Fig. 6. The Gas velocity [m/s] distribution for P_1/P_2=4 and $\dot{m}_{Fluid}$ = 8.e-4 kg/s

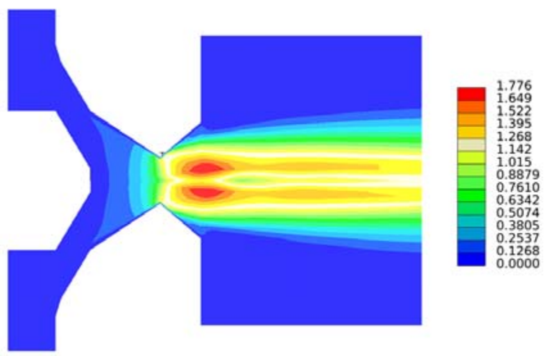

Fig. 7. Mach number distribution for P_1/P_2=4 and $\dot{m}_{Fluid}$ = 8.e-4 kg/s.

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.e-5 kg/s are presented. It is shown, that higher pressure ratios P_1/P_2 lead of a finer atomization process. Furthermore, the difference between the cases $P_1/P_2 = 3$ and $P_1/P_2 = 4$ is small.

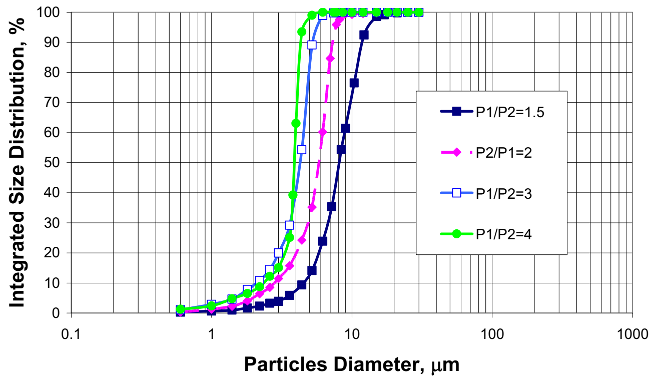

Fig. 8. Integrated particle size distribution for $\dot{m}_{Fluid}$ = 8.e-5 kg/s

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 $\dot{m}_{Fluid}$ =8.e-4 kg/s is coarser than for $\dot{m}_{Fluid}$ =8.e-5 kg/s. Additionally, a more intensive evaporation takes place for higher mass flow rates.

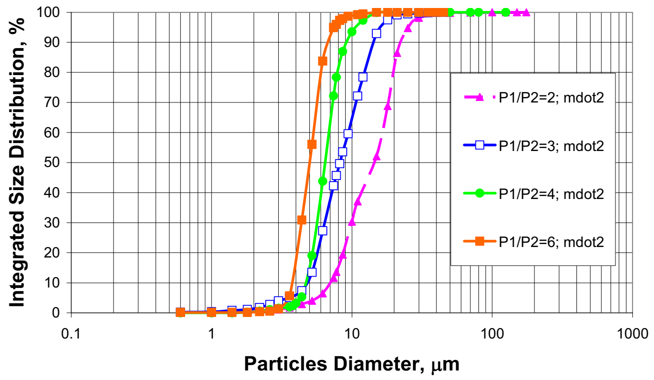

Fig. 9. Integrated particle size distribution for $\dot{m}_{Fluid}$ = 8.e-4 kg/s

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 $\dot{m}_{Fluid}$ =8.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.

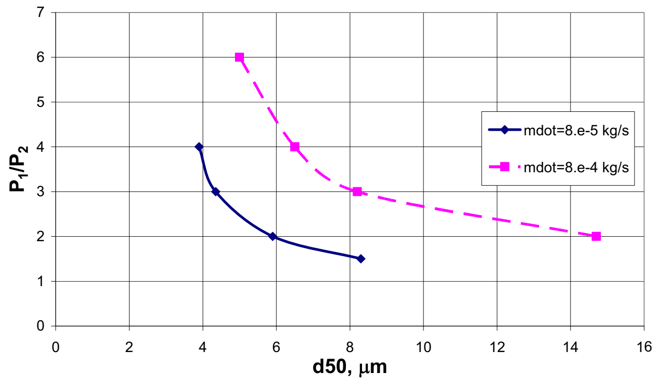

Fig. 10. Dependence between mean particles diameter and air pressure ratio.

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 $\dot{m}_{Gas} / \dot{m}_{Fluid}$ for Laval nozzle is presented. Fig. 10 and Fig. 11 reflect the phenomena that the possibility of even finer atomization for $\dot{m}_{Fluid}$ =8e.-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.

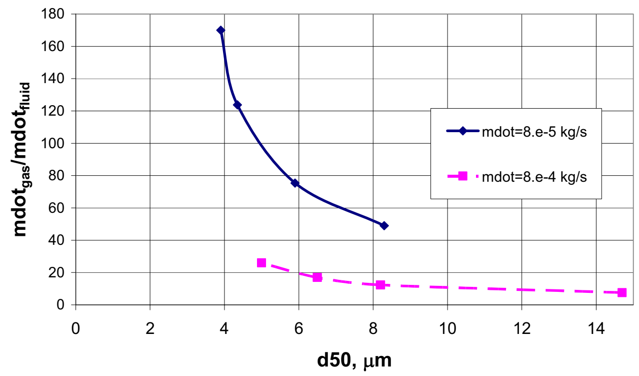

Fig. 11. Dependence between mean particles diameter and mass flow ratio $\dot{m}_{Gas} / \dot{m}_{Fluid}$.

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 $\dot{m}_{Fluid}$ 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.

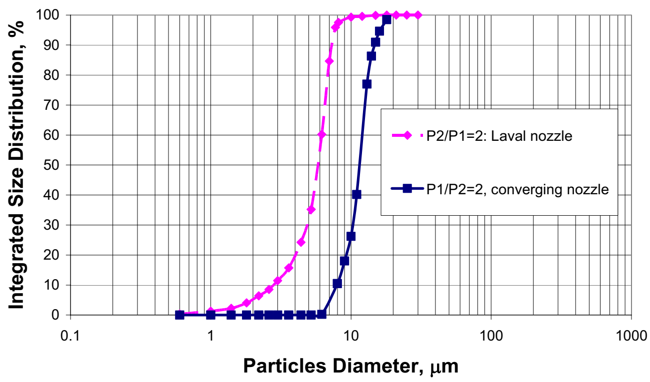

Fig. 12. Particles size distribution behind Laval and converging nozzle by $\dot{m}_{Fluid}$ =8.e-5 kg/s and P_1/P_2=2.

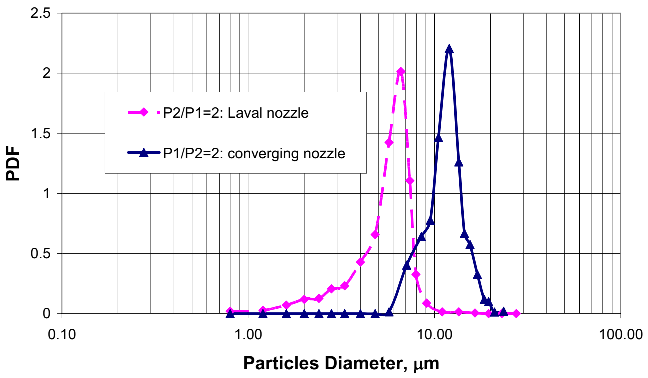

Fig. 13. Probability density distribution behind Laval and converging nozzle by $\dot{m}_{Fluid}$ =8.e-5 kg/s and P_1/P_2=2.

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 a 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.

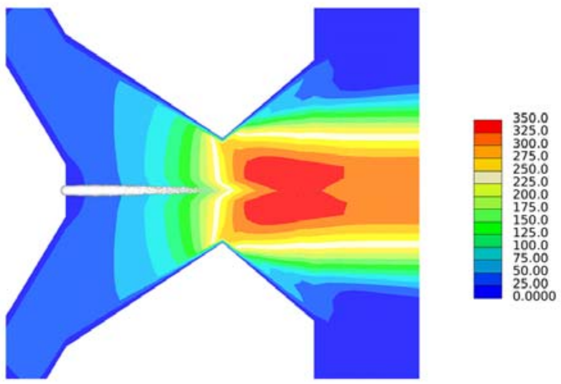

Fig.14. Laval nozzle: Distribution of gas velocity [m/s] and spray formation for $\dot{m}_{Fluid}$ =8.e-5 kg/s and P_1/P_2=2.

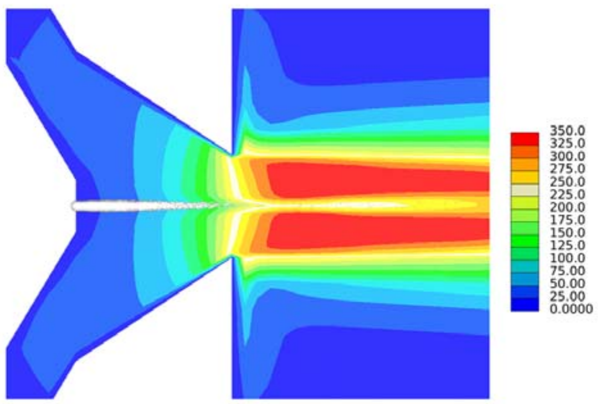

Fig.15. Converging nozzle: Distribution of gas velocity [m/s] and spray formation for $\dot{m}_{Fluid}$ =8.e-5 kg/s and P_1/P_2=2.

Behind the simplified coaxial 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 $\dot{m}_{Fluid}$ =8.e-5 kg/s is too small for this simplified geometry. The velocity distribution with spray formation for the case of $\dot{m}_{Fluid}$ =8.e-4 kg/s in Fig. 17 is presented.

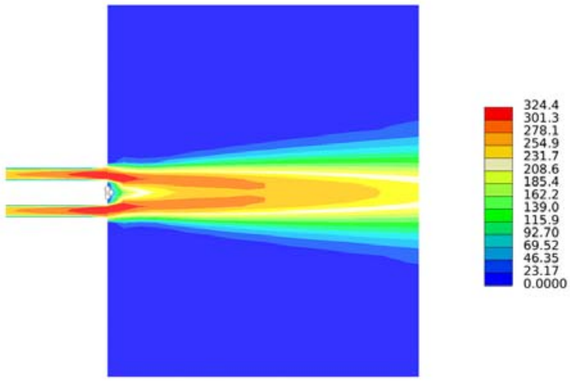

Fig. 16. Coaxial nozzle: Distribution of gas velocity [m/s] and spray formation for $\dot{m}_{Fluid}$ =8.e-5 kg/s and P_1/P_2=2.

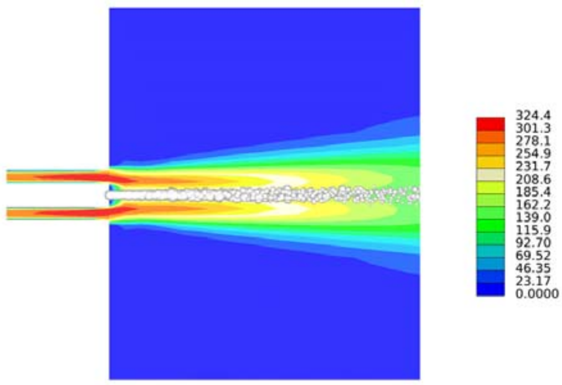

Fig. 17. Coaxial nozzle: Distribution of gas velocity [m/s] and spray formation for $\dot{m}_{Fluid}$ =8.e-4 kg/s and P_1/P_2=2.

Additionally the flow simulations with $\dot{m}_{Fluid}$ =3.e-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).

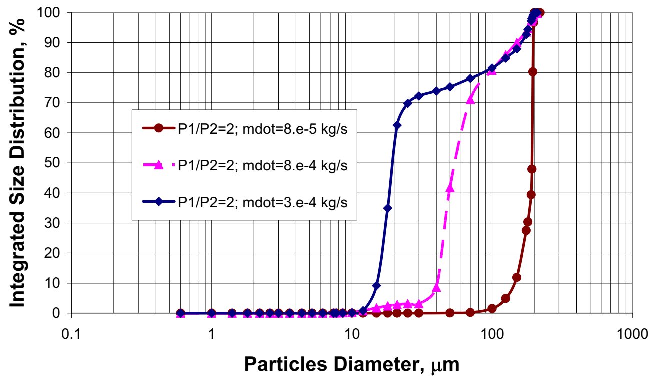

Fig.18. Particles size distribution behind coaxial nozzle.

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 $\dot{m}_{Gas} / \dot{m}_{Fluid}$. 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

Symbol	Quantity	SI Unit
P_1	Supply pressure	Pa
P_2	Chamber pressure	Pa
$\dot{m}$	Mass flow	kg/s
τ	Characteristic break-up time	s
u	Velocity	m/s
ρ	Density	kg/m³
μ	Viscosity	kg/m s
σ	Surface tension	N/m
D	Droplet diameter	m
We	We number	[-]
Oh	Ohnesorge number	[-]

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