Influence of Nozzle-Flow Turbulence on the Primary Spray Breakup

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Abstract

This paper presents experimental investigations of the correlation between nozzle flow and spray in a pressure atomizer with a constant volume flux. The focus is placed on the influence of turbulence and the secondary flow field in the nozzle. For these studies a nozzle and an operation set point were chosen such that no cavitation occurs inside the nozzle. To obtain experimental data at the same geometries for different Reynolds numbers two kind of liquids were used. In addition, various nozzle geometries have been investigated for the liquid with the lower viscosity.

Inside the transparent nozzle the three-dimensional velocity and turbulence distributions in three different cross-sections were measured using a Laser Doppler velocimetry with a high spatial resolution. To obtain information about the spray near the nozzle exit, where the optical obscuration is high, an X-ray system was developed. This system makes it possible to estimate the three-dimensional density distribution using a tomographic reconstruction process in this spray region. In the boundary area of the spray near the nozzle exit a Dual Mode phase Doppler system was applied to measure the three-dimensional velocity and droplet diameter distribution. Finally, high-speed videos from the entire spray have been taken to gain a better understanding of the spray formation.

The experimental results show that the breakup of the two liquids at different Reynolds numbers is completely different. By comparing the different nozzle geometries the turbulence was identified as the main cause for breakup. The turbulence affects the spray width and the number of droplets but it has no effect on the droplet diameter.

Introduction

For the simulation of primary atomization and the correct prediction of spray characteristics in for example diesel nozzles, the relevant physical processes have to be identified and properly modeled. In doing so an important element is to identify which properties of the nozzle flow have an influence on the primary breakup and to understand the correlations between nozzle flow and the spray near the nozzle exit. Many investigations have pointed out that cavitation, turbulence and the secondary flow field are key factors of the primary atomization.

In the work of Ganippa [1] an improved breakup was found on that side of the spray where cavitation occurred in the nozzle. Tamaki and Shimizu [2] and Hiroyasu [3] attributed the strong effects of the nozzle geometry to cavitation and increased turbulence. Badock [4] postulated that the turbulence generated in the cavitation area was responsible for promoting breakup. Also Stahl et al. [5] found enhanced spray breakup with the occurrence of very small cavitation bubbles. However, in all these studies the influence of cavitation and turbulence could not be separated, so in the present investigation only operating points with no cavitation are chosen.

Wu et al. [6] analyzed turbulent jets with shadowgraphy and postulated that the primary breakup is dominated by turbulence and surface tension. The importance of turbulence, especially in the cross-flow direction, was also mentioned by Heukelbach [7] and Walter [8].

One problem of all these investigations is that the flow field inside the nozzle could not be measured directly. In the present work the flow field and the turbulence distribution inside the nozzle was measured using a laser Doppler velocimeter (LDV) with a high spatial resolution. Under the same conditions the near nozzle regions were examined with high-speed imaging and the droplets found in the outer edges of the spray were measured with a Dual Mode phase Doppler System (PDA). Furthermore, the density distribution in the opaque spray regions was estimated applying an X-ray tomography system.

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Materials and Methods

For the present measurements a hydraulic system comprising a hydraulic power unit, a damping system, an inflow tube with the nozzle and a collection tank was used. A detailed description can be found in [9] and [10]. Since we have two different fluids (see Table 1) differing widely in viscosity we need two distinct types of pumps in the hydraulic power unit. The system operates at a constant volume flux and a constant temperature of T = 300 K. The main operating point has a volume flux of 2.0 l/min, which leads to a pressure of 1.7 ± 0.05 MPa before the nozzle in case of the Gravex 917 oil and in case of the V-Oil to a pressure of 0.9 ± 0.05 MPa. Measurements have also been performed for a volume flux of 1.0 l/min and 1.5 l/min for the V-Oil.

The laser Doppler measurements inside the nozzle require a nozzle material which has the same refractive index as the fluid. To achieve this a Plexiglas nozzle for the Gravex 917 oil and quartz glass nozzle for the V-Oil was used.

Table 1. Summary of test conditions at 2.0 l/min.

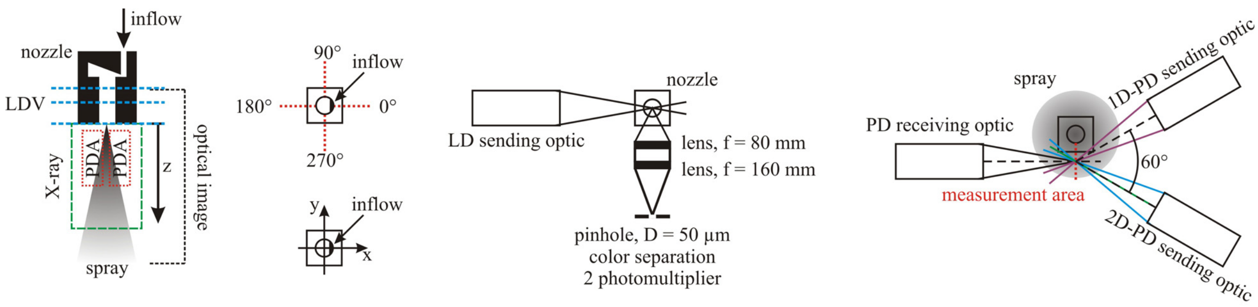
medium		Shell Gravex 917	Shell V-Oil 1404 DIN ISO 4113
density	[kg/m³]	898	826
kin. viscosity	[m²/s]	$21.0 \cdot 10^{-6}$	$2.7 \cdot 10^{-6}$
surface tension	[N/m]	$3.0 \cdot 10^{-2}$	$2.8 \cdot 10^{-2}$
Reynolds number	[-]	2000	15500
Weber number	[-]	54000	52000
Ohnesorge number	[-]	0.115	0.015

To investigate different nozzle geometries an axially symmetric reference nozzle was used into which different inlays could be placed. The reference nozzle has an approach diameter of D = 10 mm, a nozzle diameter of d = 1 mm and an orifice length of 10 mm. The inlet radius of the Plexiglas nozzle is r_{ip} = 150 µm. In order to avoid cavitation in case of the V-Oil the inlet radius for the quartz glass nozzle had to be increased to r_{iq} = 275 µm. A comparison of the flow field and turbulence level at a lower volume flux of q = 1.0 l/min for the two inlet radii showed, that this change has no significant influence for the investigated geometries.

For the flow measurements inside the nozzle a two-velocity component laser Doppler system (LDV) was used. To obtain a suitable spatial resolution inside the nozzle the detection volume has a diameter of 25 µm and length of 50 µm. The setup is shown in Figure 1 (b) and a detailed description of this system is found in [10]. Measuring in a grid of 50 × 50 µm we can measure about 300 points in a plane across the nozzle. To obtain all three components of velocity the nozzle is rotated by 90° after the first measurement of the plane and than all grid points are measured again. Due to an uncertainty of about 25 µm in the positioning of these two measurements a new center position was determined by the best correlation of the axial flow field. For all LDV measurements a system noise and spatial correction have been performed and a detailed description of these corrections can be found in [10] and [11].

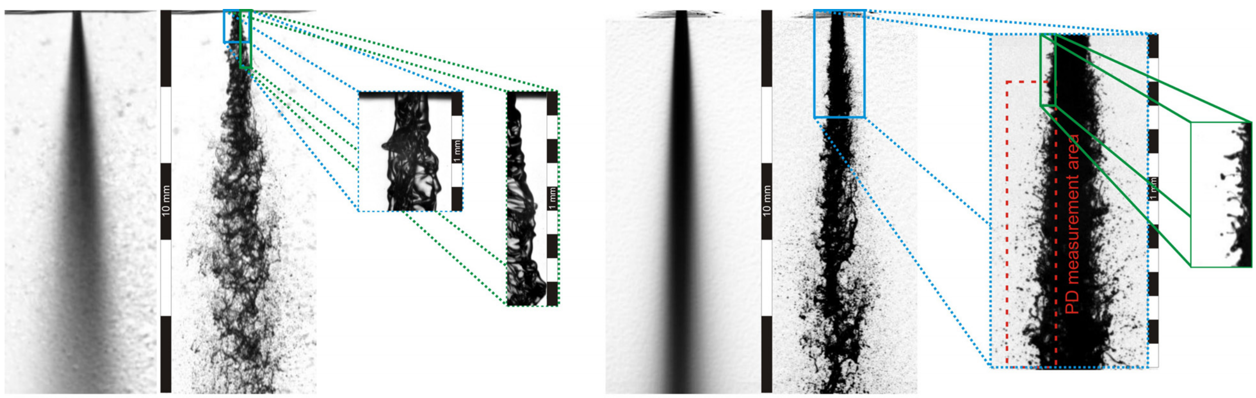
To gain a better understanding of the breakup process high-speed videos have been performed. All videos are shadow images taken with a Photron Fastcam SA1. The spray images have a field of view of 50 x 20 mm at a resolution of 10 µm/Pixel and a frame rate of 50 000 fps with a exposure time of 1 µs. In the near nozzle regions we have videos with a field of view of 14 x 7 mm at a resolution of 3 µm/Pixel and the same frame rate and exposure time as before. Finally we have videos from the spray boundary direct below the orifice exit with a field of view of 3 x 1.2 mm at and resolution of 1.6 µm/Pixel at 200 000 fps with exposure time of 1 µs.

The high-speed images from the near nozzle region of the V-Oil spray (see Figure 2 (b)) show the formation of droplets, indicating that measurements with a Phase Doppler system are possible. Ligaments in these areas make it necessary to use a Dual Mode PD-System that can validate only spherical droplets. To obtain information about the cross velocity a three-velocity component configuration of a Dantec HighDense Dual Mode PD system in full coincident mode was applied (see Figure 1. (c)). The first point we can measure is 2 mm below the orifice exit because the nozzle constrains the vertical laser beams. The area marked red in Figure 2 (b) shows the measured area in the spray, which is measured with a spatial resolution of 250 x 250 µm and 20000 samples per point. To minimize obscuration effects of the measurement position the nozzle is turned by 90° to maintain comparable conditions on all sides of the spray. Finally we measure on four sides of the spray.



(a) (b) (c)

Figure 1. Experimental setup: a) measurement positions, b) LDV-Setup and c) Dual Mode PDA setup.



(a) (b)

Figure 2. Spray images of geometry V5 with a) Shell Gravex 917 and b) V-Oil 1404.

Results and Discussion

The first part of the discussion is related to the difference between the two oils and the two Reynolds numbers. In the Ohnesorge diagram, both operation points are located in the atomization regime. Figure 2 shows pictures of the spray from the geometry V5 with long and short exposure times respectively in the first 50 mm below the nozzle, as well as short-exposure zoomed images from the near nozzle areas. In the case of Gravex 917 oil the spray is cone-shaped from the beginning and after 30 mm homogeneous distributed over the cross-section. Close to the orifice exit the spray density is higher on the right side which was also measured with X-ray tomography in [10]. For V-Oil the spray looks completely different: In the center the spray is completely opaque over the first 50 mm. This dense core is surrounded by a cloud of small droplets which are barely visible in the grayscale pictures obtained with long exposure times. Therefore the spray angle of V-Oil is dominated by the dense core which leads to a relatively small spray angle compared to Gravex 917.

The images from the near nozzle area of both liquids also show that the breakup is completely different. For Gravex the jet seems to bulge from the inner regions and than breaks up into large ligaments. For V-Oil there is a stable dense core from which jets erupt and pinch into droplets. This behavior was also observed e.g. by [6] and [12] and it is called turbulent breakup.

The only factor that can explain this completely different breakup is the viscosity, since surface tension, density, velocity and geometry are basically identical. The flow field at the orifice exit is the same for both cases and is shown in Figure 3 for V-Oil. Also the turbulence distribution is identical and the difference in the mean turbulence level is marginal with 8.0 percent for Gravex and 8.5 for the V-Oil. Moreover the surface tension of both liquids is nearly identical. It seems that for the lower viscosity the turbulent energy is high enough to develop jets at the surface which is not possible for the higher viscosity case. This result is somewhat contrary to the results of Wu [5] where the surface tension was identified as the important factor for the formation of droplets.

Table 3. Spray angle and turbulence at 2.0 l/min.

geometry Medium	V5 Gravex 917	V4 Shell V-Oil 1404	V5 Shell V-Oil 1404
spray angle x-direction [°]	10.2	4.1	5.4
spray angle y-direction [°]	7.1	2.8	3.9
Mean turbulence level [%]	8.5	6.7	8.5

In the second part of this study two different geometries (V4 and V5) operating with the V-Oil are compared. At first a comparison of the spray angle, calculated from long exposure spray images over a FWHM criterion, was performed. Both sprays have an elliptical cross section, whereas V5 has a larger spray angle and therefore a significant larger spray cross-section (see Table 3). Figure 3 shows the flow field for both geometries V4 and V5 at the orifice exit. Both geometries have two vortices of nearly the same strength. The axial flow for V4 is higher on the right side and for V5 higher on the left side. From this it follows that there is no large difference aside from the mirror imaging of the main vortex. Consequently the difference in the strength of the breakup (larger spray angle) cannot be explained by the flow field. The turbulence level calculated with respect to all three velocities and their fluctuating parts is plotted in Figure 4. It is quite clear that there is an important difference here, since the turbulence level is higher for the V5 nozzle, especially in the center of the nozzle. Averaging over the whole cross section we get a two percent higher turbulence level for V5. In summary this shows that only the turbulence level causes the differences in the strength of the breakup.

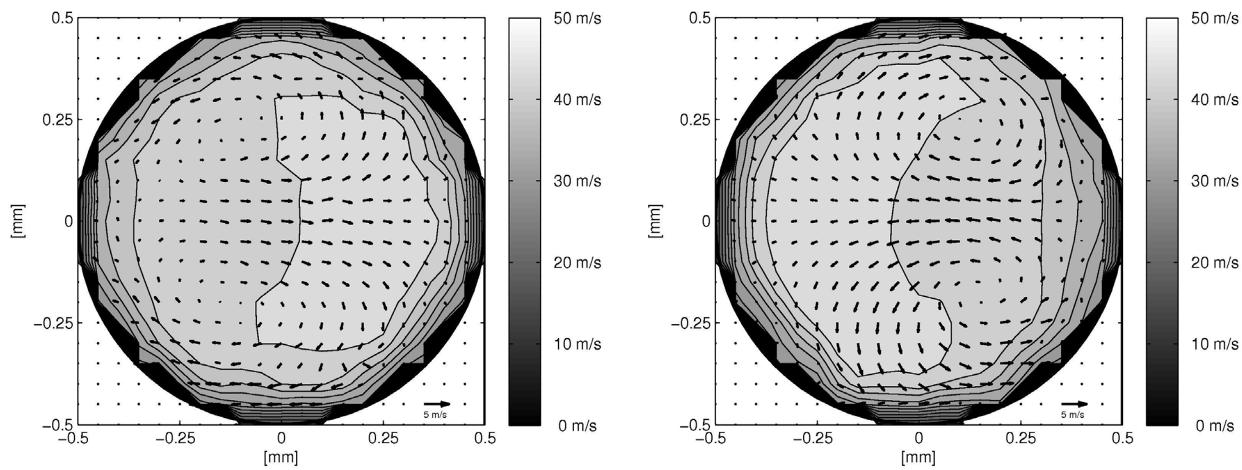


Figure 3. Flow field of geometries V4 (left) and V5 (right) in the nozzle direct at the exit.

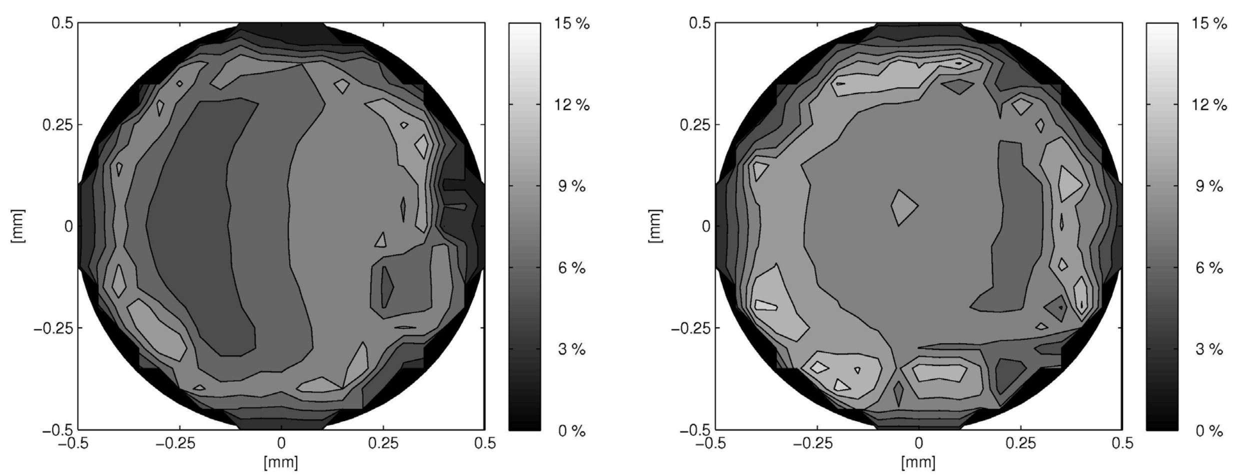


Figure 4. Turbulence level of geometries V4 (left) and V5 (right) in the nozzle direct at the exit.

To see what effects these differences have on primary breakup a closer look to the first millimeters of the spray is necessary. As mentioned before, formation of droplets occurs direct below the nozzle exit. The data rate of the PD measurements in the planes in x-direction is plotted in Figure 5. It can be seen, that in case of V4 the data rate is higher on the right side and in case of V5 on the left side whereas the total data rate for V5 is higher. This corresponds well to the area of higher turbulence at the nozzle exit and the higher turbulence values in case of V5. Estimating the middle spray width in these areas out of a decrease of the data rate (FWHM-criterion) the spray is also wider on the sides were the data rate is higher.

These results are also verified by the density distribution in the spray. In Figure 6 the density in a cross section 6.5 mm below the nozzle exit is plotted. It is clearly visible, that the density is lower in areas of higher data rate in the PD measurements and therefore higher turbulence level inside the nozzle. It can also be seen, that the overall density in case of V5 is lower compared to V4 which corresponds well to the higher mean turbulence level of the geometry V5.

The cross velocity in these spray areas is perpendicular to the core, meaning that there is no tangential motion that could be expected due to the transverse flow field inside the nozzle. Due to the different width of the sprays the position of the maximum data rate is selected to compare the cross velocity and the droplet diameters of the sprays and the positions of the measurement area. The cross velocity along these lines decreases downwards from values of about 2 m/s to 0.5 m/s whereas the values for geometry V5 are slightly higher. Overall there is no difference between the values from the different measurement planes.

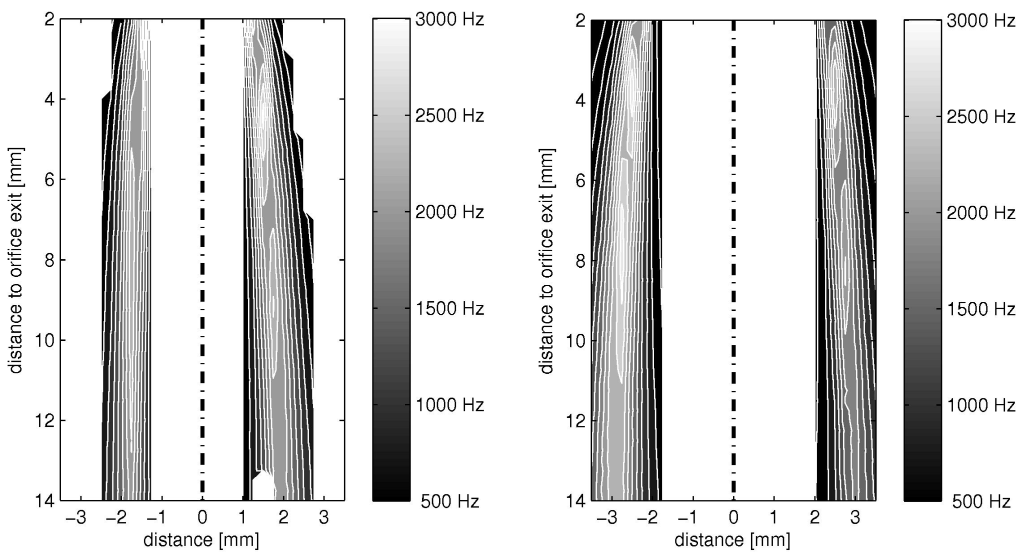


Figure 5. Data rate of phase Doppler measurements in spray of nozzles V4 (left) and V5 (right).

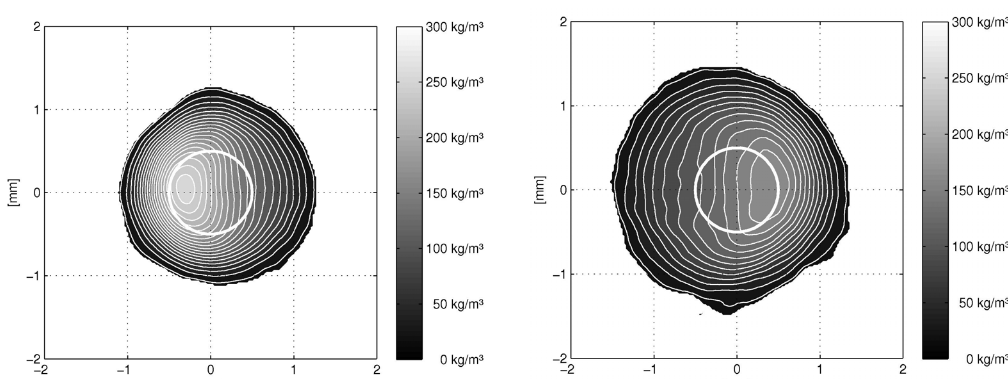


Figure 6. Density distribution in spray of nozzles V4 (left) and V5 (right) 6.5 mm below the nozzle exit.

The development of the Sauter mean diameter D_{32} along the lines of maximum data rate is shown in Figure 7 for a volume flux of 1.0 l/min, 1.5 l/min and 2.0 l/min for the geometries V4 and V5 at different measurement planes. At each volume flux no difference can be seen between the two geometries and the different measurement planes. Only a small increase of the diameter along the spray occurs. Also an increase of the diameter exists at the lower volume flux.

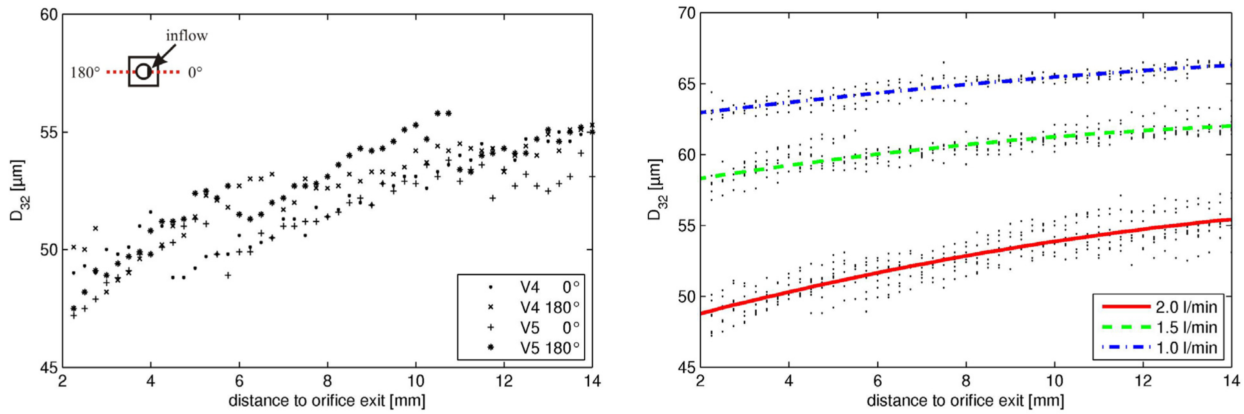


Figure 7. Development of Sauter Mean Diameter downstream of orifice: Comparison of nozzles V4 and V5 at 2.0 l/min (left) and comparison of different volume fluxes (right).

Conclusion

The influence of the secondary flow field and turbulence on primary breakup has been investigated. Measurements at the same operating point and the same geometry for different Reynolds number showed a completely different breakup mechanism - the two systems only differed in viscosity; hence Reynolds number.

For a similar flow field it could be shown that the in-nozzle turbulence level is the only factor which causes the differences in the strength of the breakup. It affects the width of the spray, the number of generated droplets and the decrease in the spray density whereas it has no significant influence on the Sauter mean diameter.

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