Experimental Investigation of High Pressure Spray Drying Nozzle Performance at Industrial Operating Conditions

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Abstract

The performance of a spray drying pressure nozzle highly depends on the operating conditions applied. Low pressure nozzles are often investigated by adjusting low volume flows in the range of a few litres per hour. In this paper it is investigated how high pressure spray drying nozzles perform at relevant industrial operating conditions. Atomizing experiments were carried out in a spray chamber using different hollow cone spray drying nozzles. Operating pressures of 200-220 bars and volumes flows of approximately 450-600 $l \cdot h^{-1}$ fluid per nozzle were applied. In addition to water as a model fluid also an industrially used process fluid (emulsion) was atomized which is of practical relevance for spray drying processes. Different measurement techniques were applied in order to perform a detailed analysis of the spray structure and the drop size and velocity distributions. In order to minimise measuring errors by droplets outside the measurement volume a special tube construction was inserted as spray splitter system into the spray cone.

1. Introduction

For fundamental research in most cases low pressure nozzles are investigated [1-3]. High pressure experiments are most often carried out with pressure nozzles for fuel injection purposes [4]. In both cases the volume flow per nozzle is limited to only a few litres per hour. Concerning the particle concentration these operating parameters ensure good conditions for spray analysis even close to the nozzle exit.

In this paper high pressure spray drying nozzles are investigated at relevant industrial operating conditions. Operating pressures of 200-220 bars and volumes flows of approximately 450-600 $l \cdot h^{-1}$ fluid per nozzle were adjusted. In this case the conditions for a detailed spray analysis are more challenging due to the high particle concentration especially in the vicinity of the nozzle tip. Nevertheless the drop size and velocity distributions could be measured by means of a special tube construction which was adapted to the spray chamber. In addition to water as a model fluid also an industrially used process fluid (emulsion) was atomized which is of practical relevance for spray drying processes.

2. Experimental Set-up

All atomization experiments were carried in a special spray chamber. Fig. 1. shows a flow scheme of the spray rig.

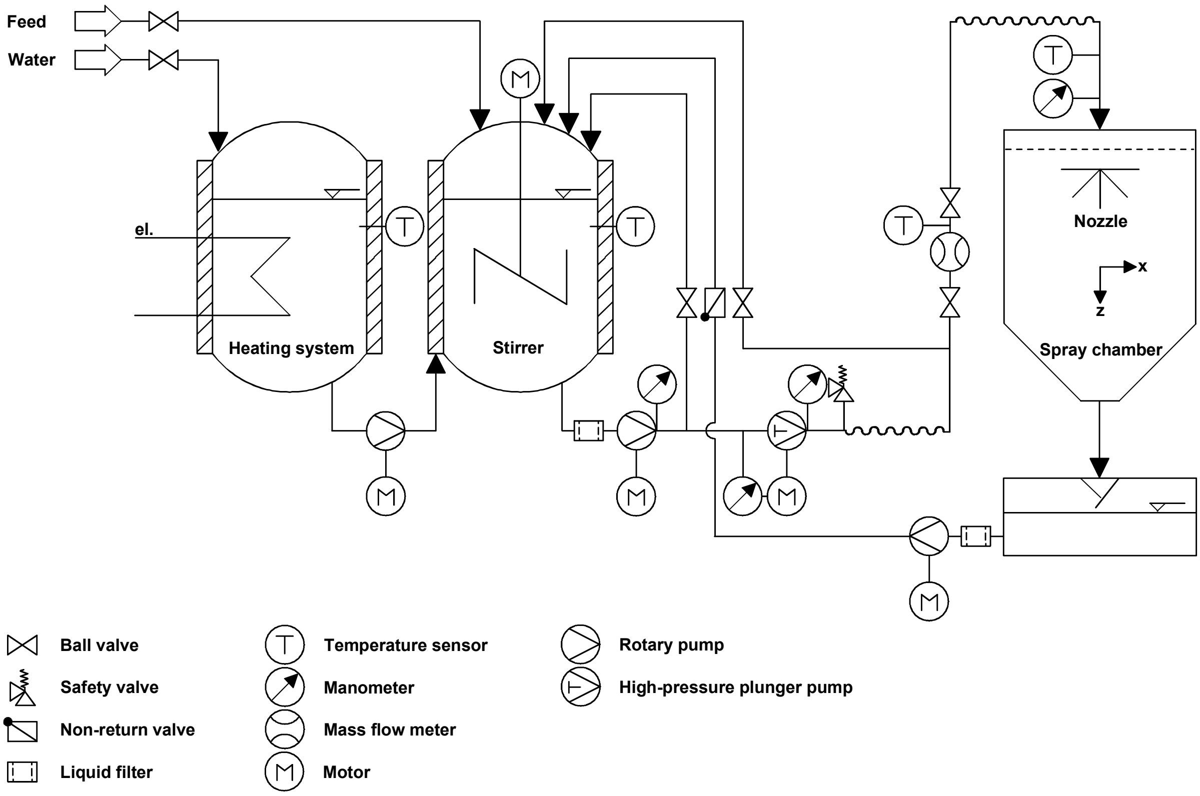
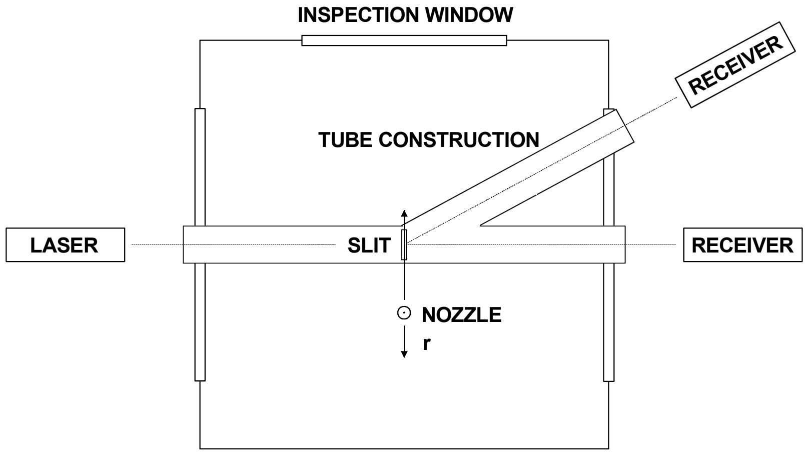


Fig. 1: Flow scheme of the pilot plant

The feed was stored in a vessel with a stirrer. The liquid was then pumped to the nozzle lance and finally atomized by the nozzle. By means of a low pressure rotary pump the sprayed liquid was returned to the storage vessel. Several control units like a high pressure mass flow meter, manometers and temperature sensors were installed to monitor the atomization process. The spray chamber was equipped with three inspection windows to give optical access to the spray.

For a detailed spray analysis several sophisticated measurement techniques were adapted to the spray chamber. The determination of the inner and outer spray angles and the global spray formation was achieved by using a specific Illumination Technique (IT) in combination with a CCD-camera. The drop size distribution was measured by means of a Diffraction Size Measurement (DSM) system at several measurement locations inside the spray cone. Additionally a Phase Doppler Anemometry (PDA) system was used to perform a more detailed analysis of the drop size and velocity distribution. Fig. 2. shows two schematic illustrations of the experimental set-up and the adapted measurement techniques.

The feed was atomized by a hollow cone nozzle (Spraying Systems, Type SB) with different swirl chambers and orifice inserts. The laser as shown in Fig. 2 was interchangeable depending on the applied measurement technique (DSM or PDA). The corresponding receivers were mounted on the opposite side of the chamber but in the same horizontal plane as the lasers. The DSM receiver was positioned in the direction of the laser beam, the PDA receiver unit was mounted with an off-axis angle of 28.5° in reference to the measurement position and the laser beam. For both laser techniques the measurement location was a fixed position in the horizontal centre of the chamber and below the slit of the tube construction. The slit had a width of 10 mm. This tube construction could be adapted to the spray chamber to minimise the influence of the particle concentration outside the measurement volume. In order to vary the measurement locations of the measurement techniques and to analyse the spray at different positions inside the spray cone, the nozzle could be moved vertically and horizontally within the chamber by means of manual traverses.



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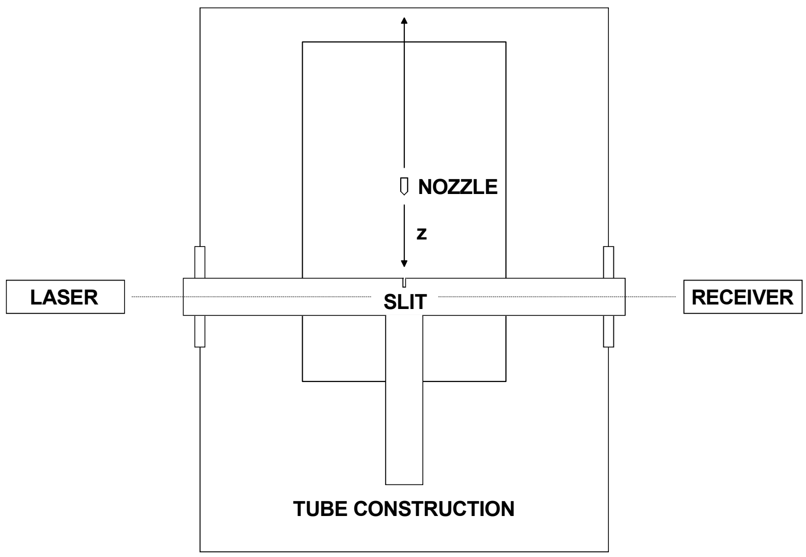

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Fig. 2: Experimental set-up with adapted measurement techniques, Top view (a), Side view (b)

3. Results and discussion

Following the datasheets of the manufacturer [5] all the investigated pressure nozzle combinations should have a hollow cone spray structure with equally distributed atomized droplets at working distance. In order to perform a differentiated analysis of the spray several measurement techniques were applied in a sophisticated manner. A special Illumination Technique (IT) was chosen to investigate the spray structure and to give an impression of the particle concentration at different locations inside the spray. Additionally a Diffraction Size Measurement (DSM) system was used to determine the droplet diameters. In order to measure simultaneously the size and the velocity of the droplets a Phase-Doppler-Anemometer (PDA) was used.

3.1. Illumination technique (IT)

As expected the pressure nozzles produced a hollow cone spray structure. Fig. 3 exemplifies a photo with the CCD-camera for one nozzle combination (Spraying Systems, Type SB, Swirl chamber No. 27 flat top, Orifice insert size No. 48, Fluid: Water, Atomization pressure: 220 bar, Volume flow: 494 $l \cdot h^{-1}$, Temperature: 19.5° C).

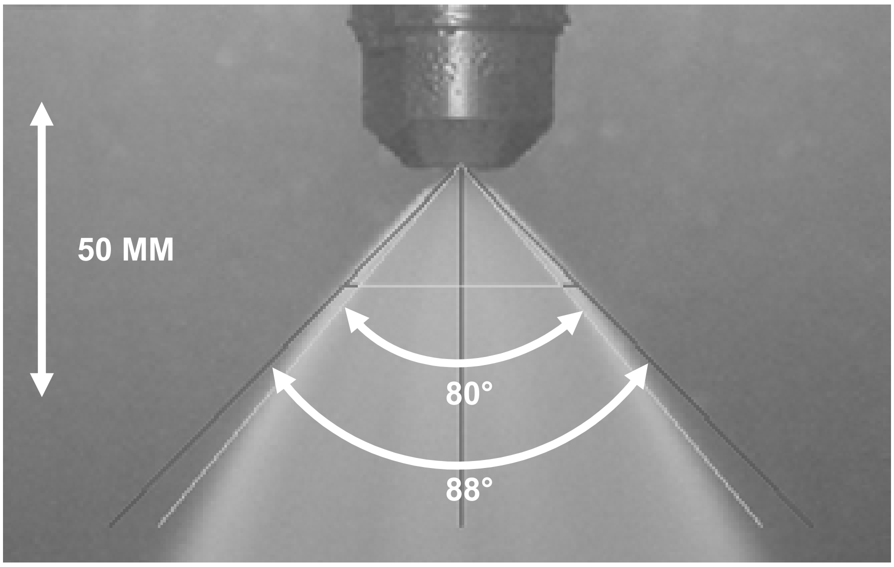


Fig. 3: Determination of inner and outer spray cone angle for one nozzle combination SB 27/48

Usually in the datasheets of nozzle manufacturers no details are given concerning the determination of the spray angle. In order to compare the investigated nozzles the inner and outer spray cone angles ISCA and OSCA were determined geometrically at a distance of $z = 10 \times d_0$ below the nozzle tip whereas d_0 is the diameter of the corresponding orifice insert. All investigated nozzle combinations showed similar hollow cone spray structure in the vicinity of the nozzle exit (Fluid: Water). The results are summarised in Table 1.

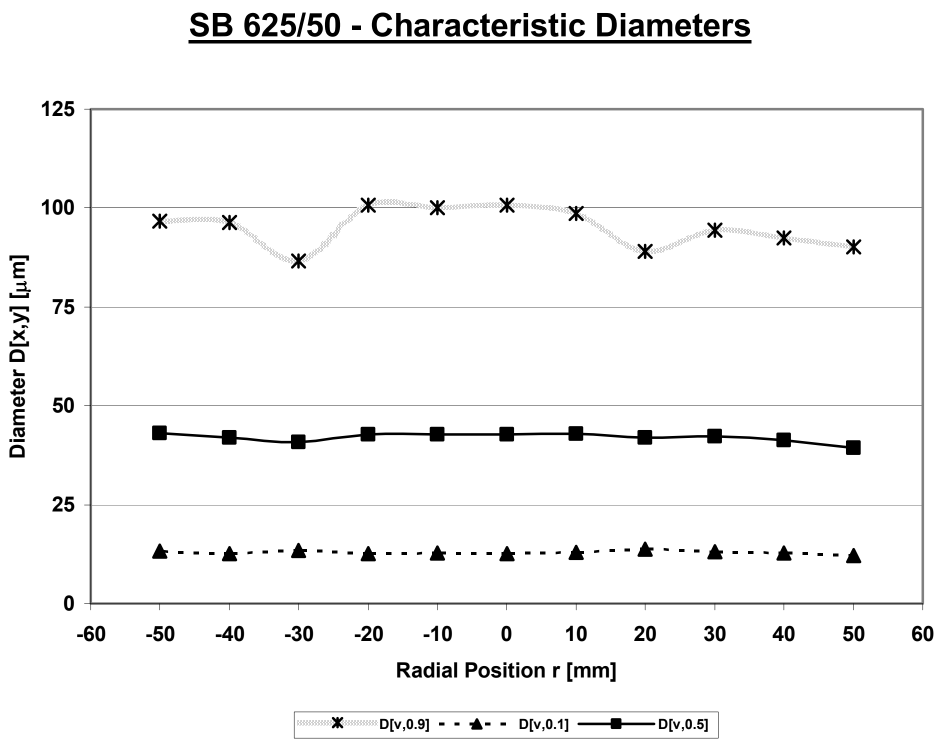
Nozzle Type	**SB**	**SB**	**SB**	**SB**	**SB**
Core size No.	32	625	625	27	27
Orifice insert size No.	52	50	53	46	48
Orifice diameter [mm]	1.61	1.77	1.51	2.05	1.93
Pressure [bar]	200.0	200.0	200.0	220.0	220.0
Volume flow [$l \cdot h^{-1}$]	598.0	554.0	448.0	543.0	494.0
Temperature [°C]	19.0	19.0	19.0	19.0	19.0
ISCA [°]	62 ± 2	68 ± 2	65 ± 2	82 ± 2	80 ± 2
OSCA [°]	71 ± 2	76 ± 2	73 ± 2	91 ± 2	88 ± 2

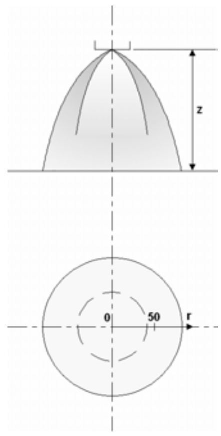
Table 1: Inner and outer spray cone angle

As can be seen from Fig. 3 the particle concentration changes from low on the axis of the spray to high in the cone segment.

3.2. Diffraction Size Measurement (DSM)

The diffraction size measurements were performed by using a Malvern 2600c system. The measurement locations were situated at a distance of z = 546 mm from the nozzle tip and at several radial positions r. At that distance from the nozzle exit the hollow cone structure of the spray does not exist any more. But still the particle concentration was very high and the tube construction was adapted to the spray chamber.





z = 546 mm

r = 0 mm
±10 mm
±20 mm
±30 mm
±40 mm
±50 mm

Fig. 4: Characteristic diameters for one nozzle combination SB 625/50

Fig. 4 shows a plot with characteristic diameters for one nozzle combination (Spraying Systems, Type SB, Swirl chamber No. 625 cup top, Orifice insert size No. 50, Fluid: Water, Atomization pressure: 200 bar, Volume flow: 554 $l \cdot h^{-1}$, Temperature: 19.5° C).
The other nozzle combinations also showed only very small variations in the characteristic diameters for all the measurement positions (Fluid: Water). The results are summarised in Table 2 whereas D[4,3] is the mean diameter over the volume distribution, D[3,2] is the Sauter Mean Diameter, D[v,0.9] is the diameter of the volume distribution at 90%, D[v,0.1] is the diameter of the volume distribution at 10% and D[v,0.5] is the median diameter of the volume distribution.

Nozzle Type	SB	SB	SB	SB	SB
Core size No.	32	625	625	27	27
Orifice insert No.	52	50	53	46	48
Orifice diameter [mm]	1.61	1.77	1.51	2.05	1.93
Pressure [bar]	200.0	200.0	200.0	220.0	220.0
Volume flow [$l \cdot h^{-1}$]	591.0	551.0	446.0	540.0	490.0
Temperature [°C]	29.0	25.0	30.0	30.0	32.0
D[4,3] [µm]	49.09	48.85	47.63	47.76	44.38
D[3,2] [µm]	26.00	25.89	24.04	27.85	27.24
D[v,0.9] [µm]	95.89	95.06	96.72	87.86	79.29
D[v,0.1] [µm]	12.86	12.92	11.39	14.81	14.99
D[v,0.5] [µm]	41.93	41.95	39.05	42.99	40.80

Table 2: Characteristic diameters for all nozzle combinations

3.3. Phase Doppler Anemometry (PDA)

A standard Phase-Doppler Anemometry system offers the possibility to measure for spherical particles simultaneously its absolute size *and* its velocity component perpendicular to the interference volume [6, 7]. For this measurement technique there exist specific error sources which affect the correct determination of size and velocity [7].
The major difficulty for the case of high pressure applications is a high particle concentration inside and outside the measurement volume. In the worst case the Doppler burst signals coming from the particles are shifted in frequency and phase difference and the determination of the droplet velocity and diameter is no longer exact [8, 9]. In order to minimise the perturbing effects of particles outside the PDA measurement volume on the signal quality in the experiments again the tube construction was adapted to the spray chamber (see Fig. 2). By means of this tube construction it was possible to measure as close as 100 mm from the nozzle exit and below. Sprays of water and a real process fluid (emulsion) were investigated. The relevant material properties of these fluids are summarized in Table 3.

Fluid	Water	Process fluid
Density [$kg \cdot m^{-3}$]	998.2	1118.0
Surface tension [$mN \cdot m^{-1}$]	72.8	42.2
Dyn. viscosity [mPa·s]*	1	16

Table 3: Material properties (* Shear rate: 1000 s^{-1}, rotational rheometer)

The density should have no major effect on the droplet size. A decrease in surface tension should decrease the droplet size but an increase in dynamic viscosity should lead to an increase in droplet size. Compared to water for the process fluid there are two opposite influencing effects and the behaviour of the droplet size can not be predicted easily.
The resulting droplet size distributions for water and process fluid are difficult to compare. This is due to a systematic broadening effect in phase difference and diameter respectively [10, 11]. But the modal values of the size distributions are expected not to be affected hardly by the broadening effect. For a distance of z = 200 mm below the nozzle tip Fig. 5 and 6 show two plots with modal diameters and modal axial velocities versus the radial position from the spray axis for one nozzle combination (Spraying Systems, Type SB, Swirl chamber No. 27 flat top, Orifice insert size No. 46, Fluid: Water/Process fluid, Atomization pressure: 220/220 bar, Volume flow: 538/538 $l \cdot h^{-1}$, Temperature: 29.7/64.2° C).

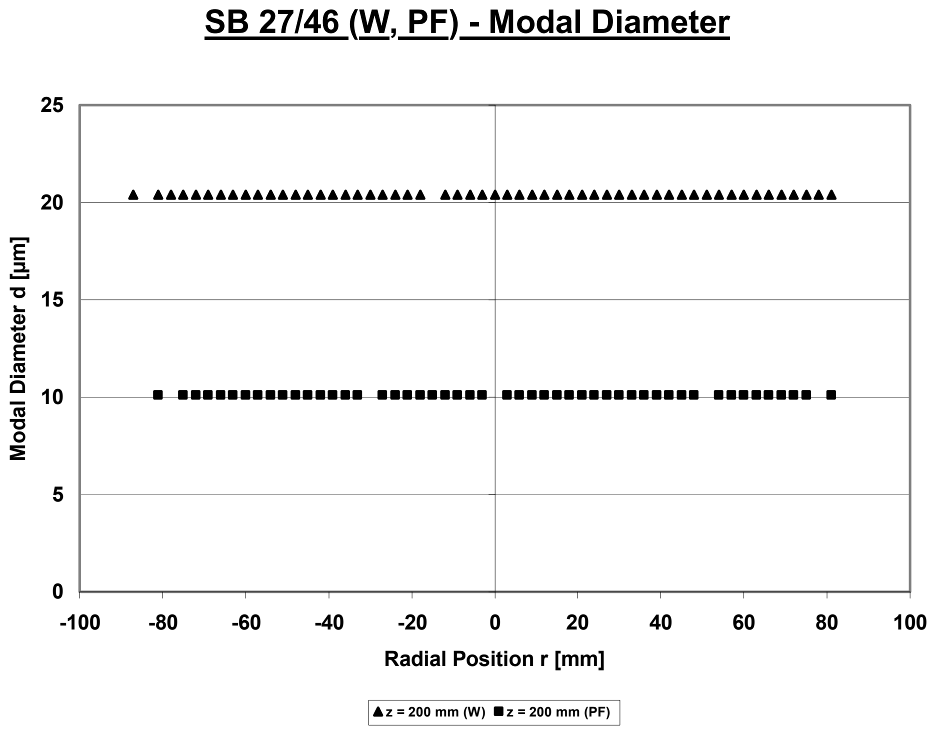


Fig. 5: Modal diameter d versus radial position r for water (W) and process fluid (PF)

The resulting modal diameters are constant for each fluid and symmetrical with respect to the spray axis. The droplet size of the process fluid is smaller than for water. Hence for these operating conditions the effect of the surface tension on the drop size seems to be more dominant than the influence of the dynamic viscosity.

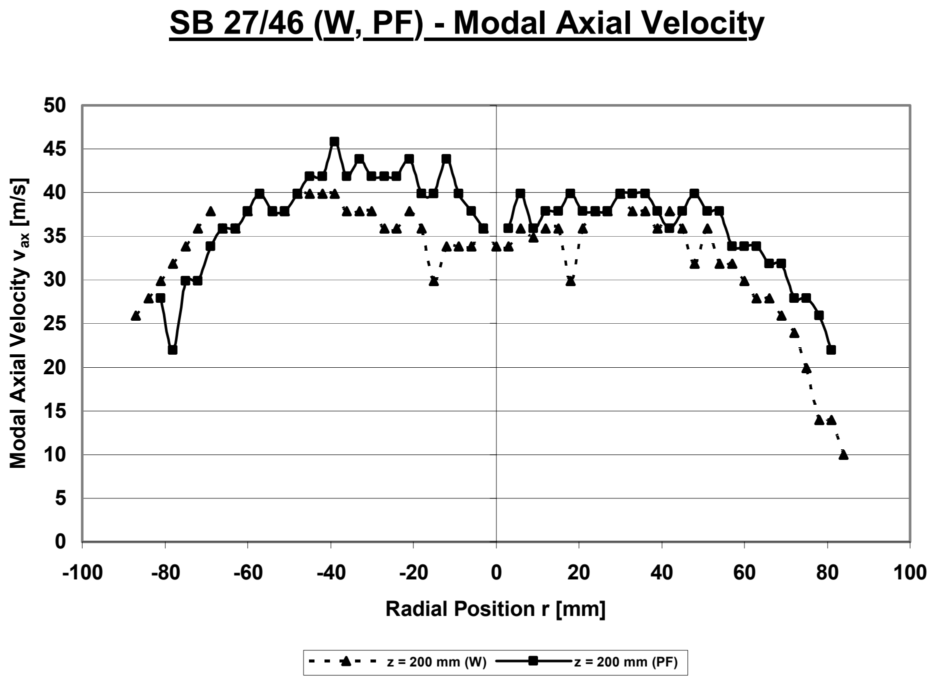


Fig. 6: Modal axial velocity v_{ax} versus radial position r for water (W) and process fluid (PF)

Concerning the measured profiles of the axial velocity no broadening effect is expected. This can be seen from Fig. 6. Again the profiles are symmetrical with respect to the spray axis and almost identical for both fluids with only small deviations. The decrease in axial velocity with increasing radial distance is due to the decelerating influence of the surrounding air at the boundary of the spray structure.

4. Summary

In this paper it was investigated how hollow cone pressure swirl atomizers perform at industrial operating conditions of 200-220 bars and volume flows of 450-600 $l \cdot h^{-1}$. By means of a special tube construction which was adapted to the spray chamber it was possible to minimise the influence of the particle concentration close to measurement volume of the applied laser measurement techniques and to measure at a distance of z = 100 mm and below the nozzle exit. Water as a model substance and an industrially spray dried process fluid (emulsion) were atomized. All nozzles showed a hollow cone spray structure in the vicinity of the nozzle exit. At a distance of z = 200 mm below the nozzle tip for both fluids the modal diameters are almost constant with increasing radial distance from the nozzle axis. The modal diameters of the process fluid is smaller than for water due to the dominant effect of surface tension on drop size for these specific operating conditions. The decrease in axial velocity with increasing radial distance is caused by the decelerating influence of the surrounding air at the boundary of the spray cone.

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