Cavitation patterns in high-pressure homogenization nozzles with cylindrical orifices: Influence of mixing stream in Simultaneous Homogenization and Mixing

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Abstract

High-pressure homogenization is the state of the art to produce high-quality emulsions with droplet sizes in the submicron range. In simultaneous homogenization and mixing (SHM), an additional mixing stream is inserted into a modified homogenization nozzle in order to create synergies between the unit operation homogenization and mixing. In this work, the influence of the mixing stream on cavitation patterns after a cylindrical orifice is investigated. Shadow-graphic images of the cavitation patterns were taken using a high-speed camera and an optically accessible mixing chamber. Results show that adding the mixing stream can contribute to coalescence of cavitation bubbles. Choked cavitation was observed at higher cavitation numbers σ with increasing mixing stream. The influence of the mixing stream became more significant at a higher orifice to outlet ratio, where a hydraulic flip was also observed at higher σ . The decrease of cavitation intensity with increasing back-pressure was found to be identical with conventional high-pressure homogenization. In the future, the results can be taken into account in the SHM process design to improve the efficiency of droplet break-up by preventing cavitation or at least hydraulic flip.

Keywords

high-pressure homogenization
cavitation
simultaneous homogenization and mixing (SHM)
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1 Introduction

High-pressure homogenization is the state of the art to produce high-quality emulsions with droplet sizes in the submicron range in the pharmaceutical, chemical, and food industry. A raw emulsion is compressed to pressures up to 1000 bar or higher and then accelerated through a disruption unit. While different kinds of disruption units such as flat valves or orifice nozzles are used in homogenizers, they all have a strong reduction of the flow cross section in common (Schuchmann, 2016). As a result, disruptive stresses such as elongational stress, shear stress, or turbulent inertial stress causing droplet breakup are induced in laminar, transitional, or turbulent flow (Walstra, 1993; Kelemen et al., 2015).

Furthermore, hydrodynamic cavitation can occur in and after the constriction due to a local pressure drop (Franc and Michel, 2005). It is defined as the spontaneous emergence, growth, and subsequent implosion of vapor filled cavities.

The collapse of cavitation bubbles near a droplet can lead to the formation of a microjet focused at the bubble and cause droplet breakup. The occurrence of cavitation also changes the local flow conditions and effects the hydrodynamic stresses. In previous works, several cavitation patterns were observed in high-pressure homogenization nozzles (Schlender et al., 2015b; Gothsch et al., 2016). Depending on the applied pressures and the ratio of orifice diameter to outlet diameter β , jet cavitation, choked cavitation, and hydraulic flip were observed. It was found that the cavitation pattern affects the efficiency of droplet breakup in emulsification processes and the occurrence of a hydraulic flip proved to be especially harmful for the droplet breakup (Schlender et al., 2015b). By applying a back-pressure after the orifice at the same inlet pressure, visible cavitation decreases. This correlation was first shown by McKillop et al. (1955). When the ratio of back-pressure to inlet pressure described as Thoma number reaches $0.3 < Th < 0.5$ depending

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Nomenclature

d_{inlet}	diameter of orifice inlet (mm)	p_{inlet}	pressure at orifice inlet (bar)
d_{orifice}	diameter of orifice (mm)	p_2	pressure applied downstream the orifice (bar)
d_{outlet}	diameter of orifice outlet (mm)	p_{vapor}	vapor pressure (bar)
HPH	high-pressure homogenization	SHM	simultaneous homogenization and mixing
$\dot{M}_{\text{HS}}$	mass flow rate of high-pressure stream (kg/s)	Th	Thoma number (—)
$\dot{M}_{\text{MS}}$	mass flow rate of mixing stream (kg/s)	$u_{\text{HS, inlet}}$	velocity at orifice inlet (m/s)
$\dot{M}_{\text{total}}$	total mass flow rate (kg/s)	$u_{\text{MS, inlet}}$	velocity at mixing stream inlet (m/s)
OAMC	optically accessible mixing chamber	β	ratio of orifice to outlet diameter (—)
p	pressure (bar)	σ	cavitation number (—)

on the geometry, cavitation disappears (Jahnke, 1998). Amongst others, Kurzahls and Reuter (1979), Freudig et al. (2003), Finke et al. (2014), and Schlender et al. (2015a) were able to enhance droplet breakup efficiency in emulsification trials by applying a back-pressure with a minimum droplet size located at 20%–30% of the inlet pressure.

However, conventional high-pressure homogenization is still very energy consuming and not applicable for some material systems. By adding an additional mixing stream into the homogenization nozzle shortly after the orifice, new applications and energy reductions could be achieved (summarized in Gall et al. (2016)). This development is called simultaneous homogenization and mixing (SHM) (Köhler und Schuchmann, 2012). For example, it can be used to improve energy efficiency in milk homogenization by preventing coalescence by diluting the premix using a mixing stream of skim milk (Köhler et al., 2007). At the present time, it is not fully understood how adding the mixing stream changes the flow conditions in the SHM nozzle. So far, no cavitation investigations have been carried out including a mixing stream. Since adding the mixing stream causes an increase of the total mass flow and could lead to a local increase of pressure, it possibly changes the cavitation pattern if not reduce cavitation intensity. This assumption is supported by the fact that increasing the Th number did not affect the drop size distribution in the SHM process as strongly as in conventional HPH in milk homogenization (Köhler et al. 2009).

The aim of this work is therefore to investigate the influence of the mixing stream on the occurrence and pattern of cavitation. As a first step, it is examined whether cavitation in SHM can also be prevented by applying the same Th numbers as in conventional high-pressure homogenization. Since applying a back-pressure increases energy consumption in SHM due to the increased pressure needed for conveying the mixing stream, the influence of the mixing stream on cavitation patterns obtained without applying back-pressure is also investigated. Optical

investigations of cavitation have been conducted in the past using incident lighting (de Giorgi et al., 2013), laser light induced luminescence combined with mikro-PIV (Gothsch et al., 2016), or via sono-chemiluminescence (Schlender et al., 2016).

The cavitation patterns in this study are observed taking shadow-graphic images using opposing light at several process parameters as presented by Sato et al. (2013). For the trials, a modified homogenization nozzle with optically accessible mixing chamber (OAMC) was built, which enables the visualization of cavitation after the orifice throat.

2 Theoretical background

In order to describe the results obtained in this study, several established approaches will be applied. Based on the continuity equation through an orifice, the mean velocity in the orifice $\bar{u}_{\text{orifice}}$ through an orifice with diameter d_{orifice} is calculated as follows:

$$\bar{u}_{\text{orifice}} = \frac{\dot{M}_{\text{HS}}}{\pi \cdot \left(\frac{d_{\text{orifice}}}{2} \right)^2 \cdot \rho_1} \quad (1)$$

In this case, the mass flow rate $\dot{M}_{\text{HS}}$ through the orifice can be experimentally measured and ρ_1 represents the density of the liquid at experimental conditions. With the dynamic viscosity of the liquid η_1 and $\bar{u}_{\text{orifice}}$, the Re number in the orifice:

$$Re_{\text{orifice}} = \frac{\rho_1 \cdot d_{\text{orifice}} \cdot \bar{u}_{\text{orifice}}}{\eta_1} \quad (2)$$

can be calculated to estimate the flow regime.

In high-pressure processes with an increased back-pressure, the ratio between the applied back-pressure p_2 and inlet pressure p_{inlet} is often used to describe homogenization results at different parameters (Kurzahls and

Reuter, 1979). It is defined as Thoma number

$$Th = \frac{p_2}{p_{\text{inlet}}} \quad (3)$$

In this case, the pressures are given as relative pressures resulting in $Th = 0$ describing a process without applied back-pressure. Especially for processes with no or low back-pressure, the cavitation number σ is much more precise to describe cavitation patterns. It describes the probability of cavitation appearance in an orifice throat and its outlet channel (Numachi et al., 1960). It is calculated on the basis of the ration between the static pressure tending to suppress cavitation and the hydrodynamic pressure tending to support cavitation (Stanley, 2012):

$$\sigma = \frac{p_2 - p_{\text{vapor}}(T_1)}{0.5 \rho_1 \cdot \bar{u}_{\text{orifice}}^2} \quad (4)$$

Here, p_2 describes the pressure downstream of the orifice, which equals p_2 for trials with applied back-pressure and the atmospheric pressure otherwise, and $p_{\text{vapor}}(T_1)$ is given by the vapor pressure for the used liquid at its temperature. While cavitation can initiate when falling below $\sigma = 1$, the number of cavitation bubbles and collapses increase with decreasing σ .

The cavitation number at which the first small cavitation bubbles can be observed is characterized as cavitation inception σ_i , which strongly depends on the geometrical aspects of the orifice described by d_{outlet} , d_{orifice} , and their ratio $\beta = \frac{d_{\text{orifice}}}{d_{\text{outlet}}}$. Mishra and Peles (2005) measured $\sigma_i =$

0.1–0.5 in a micro-orifice with $d_{\text{orifice}} = 11.5 \mu\text{m}$ and $\beta = 0.1$. With decreasing σ , more cavitation bubbles occur and expand while traveling downstream with the flow (Sato and Saito, 2002; Mizuyama et al., 2010). When the cavitation bubbles are visible downstream the orifice in the shape of a jet consisting of single bubbles, the cavitation pattern is described as jet cavitation or cavitating jet (Soyama et al., 1996). The cavitation pattern in which the first coherent vapor bubble appears is called choked cavitation and located at σ_{ch} (Yan and Thorpe, 1990). It can be calculated using the following equations:

$$\sigma_{\text{ch}} = 2\beta^4 \left(\frac{1}{C_c \cdot \beta^2} - 1 \right) \quad (5)$$

$$C_c = \frac{A_{\text{eff}}}{A} \quad (6)$$

The concentration coefficient describes the ratio between the real orifice flow area A and the effective orifice flow area A_{eff} (Stephan et al., 2019) due to the “vena contracta” at the entrance of the orifice. Choked cavitation can merge

into the cavitation pattern “hydraulic flip” by decreasing σ or increasing β (Schlender et al., 2015b), which occurs when the outlet channel is filled completely by one cohesive vapor bubble surrounded by a thin liquid film (Sou et al., 2007).

3 Materials and methods

3.1 Materials

Distilled water was used as a model system for both the experiments and simulations. Schlender et al. (2015b) was able to show that adding a surfactant can prevent coalescence of single cavitation bubbles, but does not influence the length and change of cavitation patterns. Their trials also showed that adding plant oil up to 10 wt% to water with adjusted refractive index showed no influence on the cavitation pattern. Furthermore, the water used in the experiments was not degassed. This could potentially lead to the occurrence of pseudocavitation, which is described as diffusion of dissolved air due to the decrease in local pressure. While Tesch (2002) stated that pseudocavitation plays a minor part at $\sigma \ll 1$, the results observed in this study could present an overlay of pseudocavitation and hydrodynamical cavitation. We decided to work with non degassed distilled water for the following reasons:

- By not degassing the water, the results reflect real process conditions in high-pressure homogenizers better.
- The results presented in this study can be compared to findings in literature (Gothsch et al., 2015; Schlender et al., 2015b).

3.2 High-pressure homogenization plant setup

A schematic of the experimental plant setup is given in Fig. 1. For conveying the high-pressure stream, distilled water is prepared in a storage tank (A) and then compressed by a two-piston pump with a working pressure of 1200 bar. A

Fig. 1 Experimental plant setup: (A) storage tank high-pressure stream, (B) two-piston pump, (C) pulsation damper, (D) disruption unit, (E) pressure tank, (F) reducing valve, (G) nitrogen tank, (H) needle valve, (I) needle valve, (J) storage-tank outlet stream. The plant can be operated with (setup a) or without (setup b) applying back-pressure with a needle valve.

pulsation damper (C) compensates for pressure fluctuations. The mixing stream is conveyed by regulating the pressure in a pressure tank (E) with a nitrogen bottle (G) and a reducing valve (F). A needle valve (H) enabled to adjust the mass flow rate of the mixing stream accordingly to the high-pressure stream achieving the desired mixing ratio. Both streams are mixed in a disruption unit with optically accessible mixing chamber (OAMC). The disruption unit is made via drilling and consists of two parts as illustrated in Fig. 1.

The pipe supply of the high-pressure stream and the circular orifice are made of stainless steel to guarantee their pressure resistance. The orifice is followed by an optically accessible mixing chamber (OAMC) made of PMMA (Fig. 2). This design enables the investigation of cavitation after the orifice while cavities in the orifice throat itself remain invisible. The insertion of the mixing stream to the circular outlet is designed as a T-mixer shortly after the orifice. For trials in which cavitation patterns were observed in the outlet channel

with $d_{\text{outlet}} = 2 \text{ mm}$ and $\frac{\dot{M}_{\text{MS}}}{\dot{M}_{\text{HS}}} = 0$, an outlet channel without

a T-mixer was used to prevent cavitation bubbles flowing back in and out of the T-mixer and thus changing the cavitation pattern. The geometrical aspects of the disruption unit used for the trials and the simulations are specified in Table 1.

For the trials that required an increased back-pressure after the disruption unit, a needle valve (I) was used (setup a) to reduce the flow cross section. In the remaining trials, the outlet pressure after the orifice p_2 corresponded to atmospheric pressure.

3.3 Experimental procedure for capturing shadow-graphic images

The cavitation patterns were visualized using opposing light imaging (shadow-graphic) as performed in literature (Sato

Fig. 2 Schematic diagram of disruption unit consisting of two parts: (1) orifice inlet and throat made of steel, (2) optically accessible mixing chamber made of PMMA.

Table 1 Geometrical aspects of the homogenization unit

Geometrical aspect	Abbreviation	
Orifice diameter	d_{orifice}	150 μm
Orifice length	l_{orifice}	400 μm
Inlet cone angle	α_{in}	59°
Outlet cone angle	α_{out}	90°
Inlet diameter	d_{inlet}	1.5 mm
Diameter of optically accessible unit	d_{outlet}	2 mm; 4 mm
Length of optically accessible unit	l_{outlet}	40 mm
Distance between orifice outlet and mixing stream insertion	a	4.5 mm

et al., 2013; Schlender et al., 2015b). As light source, a LED lamp (Constellation 120 E, IDT Inc., Florida, USA) was installed on the opposite site of the camera. The OAMC was coated with a diffuse film to even out the light. The high-speed camera OS3-S3 (IDT Inc., Florida, USA) combined with a 100 mm macro objective (Canan Inc., Japan) was used to take pictures of the cavitation patterns in the OAMC. The frequency of the recording was set to 10,000 fps and the exposure time ranged between 50 and 70 μs . For each set of parameters, 2000 images were taken. Since the cavitating flow fluctuates in time, the image series was converted to gray images in MATLAB (Matlab Inc, USA) and processed to an averaged image. While representative single images are used to discuss the cavitation pattern in detail, the averaged image provides information on the average shape of the cavitation pattern, e.g., the length of the jet in jet cavitation.

In order to investigate the effect of the mixing stream on different cavitation patterns, the inlet pressure p_{inlet} of the high-pressure stream was varied between 100 and 550 bar. Since the orifice diameter $d_{\text{orifice}} = 150 \mu\text{m}$ was kept constant for all trials, an increase of the inlet pressure is directly connected to an increase of the Re numbers in the orifice Re_{orifice} . The values for Re_{orifice} were calculated and are given in Table 2. However, the discussion of the experiments will be based on the inlet pressures as these contribute to the calculation of the characteristic numbers.

A set of trials was conducted to investigate the influence of an increased Th number on the disappearance of visible cavitation. The Th number was adjusted between 0 (which equals no applied back-pressure) and 0.25. Since the Th number is only commonly used in high-pressure homogenization, the cavitation number σ was also calculated for all sets of parameters. For this, the vapor pressure $p_{\text{vapor}}(20^\circ\text{C}) = 0.02347 \text{ bar}$ was used (Stephan et al., 2019). In the trials, the temperature ranged between 20 and 40 $^\circ\text{C}$. In that area, the increase of the vapor pressure in this temperature range does barely influence σ and was therefore neglected.

Table 2 Measured mass flow rates and calculated characteristic values

p_{inlet} (bar)	p_2 (bar)	$\dot{M}_{\text{HS}}$ (kg/s)	$\bar{u}_{\text{orifice}}$ (m/s)	Re_{orifice} (—)	σ (—)
100	0	0.00171	97.1	16,320	0.021
100	1	0.00171	97.1	16,320	0.042
100	5	0.00171	97.0	16,320	0.128
100	10	0.00172	97.7	16,410	0.149
100	15	0.00168	95.3	16,010	0.353
100	20	0.00170	96.5	16,220	0.452
100	25	0.00170	96.5	16,220	0.559
100	30	0.00163	92.6	15,570	0.725
100	40	0.00150	84.9	14,270	1.141
100	50	0.00140	79.1	13,300	1.632
150	0	0.00200	113.5	19,070	0.0154
200	0	0.00232	131.7	22,130	0.0114
250	0	0.00262	148.7	24,990	0.0090
300	0	0.00284	161.2	27,090	0.0076
400	0	0.00340	193.0	32,430	0.0053
450	0	0.00362	205.2	34,480	0.0047
500	0	0.00384	217.9	36,620	0.0042
550	0	0.00402	228.16	38,340	0.0038

As it is to be expected that the effect of the mixing stream strongly depends on the mixing ratio $\frac{\dot{M}_{\text{MS}}}{\dot{M}_{\text{HS}}}$, it was varied

between 0 (no mixing stream) and 20. Because the mixing stream is not considered in any of the characteristic numbers, they only depend on p_{inlet} and p_2 .

Furthermore, the trials were conducted using two outlet diameters d_{orifice} at 2 and 4 mm, resulting in $\beta = 0.075$ and $\beta = 0.038$. The reason for this is that the increase of total mass flow with increasing $\frac{\dot{M}_{\text{MS}}}{\dot{M}_{\text{HS}}}$ could affect the cavitation patterns more significant at a lower outlet diameter and therefore higher β .

4 Results and discussion

The results presented in this study show how the mixing stream in SHM nozzles influences cavitation. The first part deals with the question whether applying a back-pressure affects visible cavitation in the same way as described in literature for conventional HPH nozzles. First, shadow-graphic images are taken under variation of the Th number. These results are supplemented by local pressure distributions calculated in simulations in order to assess their validity with regard to predict cavitation. The second part describes

in detail how increasing the mixing stream at constant high-pressure homogenization stream affects different cavitation patterns and their transitions using shadow-graphic images.

4.1 Influence of back-pressure on shadow-graphic images

In order to verify that the effect of decreasing visible cavitation with increasing back-pressure is comparable to conventional high-pressure homogenization, shadow-graphic images were taken at $Th = 0$ –0.25 for two inlet pressures. Figure 3 visualizes the cavitation pattern obtained for

$\beta = 0.075$ and $\frac{\dot{M}_{\text{MS}}}{\dot{M}_{\text{HS}}} = 1$. It is remarkable that although the cavitation patterns strongly differ at $Th = 0$, they appear identical at increased Th numbers.

While the cavitating jet observed at $p_{\text{inlet}} = 100$ bar and $Th = 0$ decreases in length and diameter for increasing Th , the vapor bubble completely filling out the channel for $p_{\text{inlet}} = 200$ bar and $Th = 0$ also transitions to jet cavitation already at $Th = 0.01$. The Th number proves to be decisive for the jet length of visible cavitation bubbles for this set of parameters. At $Th = 0.25$ and $\sigma \approx 0.56$ –0.59, cavitation bubbles are not longer visible in the OAMC. Due to the invisible orifice throat, the disappearance of visible cavitation bubbles can only be referred to the disappearance of bubbles visible in the OAMC while they could still occur in the orifice throat. These results confirm that cavitation can be reduced by applying a back-pressure in SHM disruption units as already shown for conventional HPH (Schlender et al., 2016).

The reduction of the cavitating jet at $\frac{\dot{M}_{\text{MS}}}{\dot{M}_{\text{HS}}} = 1$ was also directly compared to trials in which no mixing stream was added in Fig. 4. In this case, β was set to 0.038.

Fig. 3 Influence of back-pressure on supercavitation as a function of inlet pressure and Th for $\beta = 0.075$ and $\frac{\dot{M}_{\text{MS}}}{\dot{M}_{\text{HS}}} = 1$.

The cavitation intensity decreases with increasing Th number and visible cavitation disappears at $Th = 0.25$ for both inlet pressures.

Fig. 4 Influence of back-pressure on visible cavitation as a function of mixing ratio and Th for $\beta = 0.038$ and $p_{\text{inlet}} = 100$ bar. Adding the mixing stream does not change the visible effect of the applied back-pressure.

With increasing back-pressure, the visible supercavitation in the orifice outlet disappeared at $Th = 0.25$ and $\sigma = 0.559$. It is clearly visible that the length of the visible cavitating jet at applied back-pressure is not influenced by adding a mixing stream at $\frac{\dot{M}_{\text{MS}}}{\dot{M}_{\text{HS}}} = 1$. For this reason, it can be assumed

that the values for Th found in literature required for disappearance of visible cavitation are also valid for SHM nozzles. Schlender et al. (2016) observed the disappearance of visible cavitation in shadow-graphic images at $Th = 0.28$ using an orifice with a slightly larger diameter of $d_{\text{orifice}} = 224 \mu\text{m}$ (Schlender et al., 2016). A comparison with the images shown above also shows that the disappearance of visible cavitation does not depend on β . In summary, no influence of the mixing ratio could be observed in this case.

4.2 Influence of mixing ratio on cavitation patterns

4.2.1 Influence of mixing ratio on jet cavitation

This section visualizes the impact on an increasing mixing ratio $\frac{\dot{M}_{\text{MS}}}{\dot{M}_{\text{HS}}}$ on jet cavitation. Figure 5 shows the change of the cavitating jet at $p_{\text{inlet}} = 100$ bar and $\beta = 0.075$. For a better visibility of the effects, for each mixing ratio ranging between 1/5 and 20, both an instantaneous impression is given by a single image (“instantaneous”) and the averaged image shows that the observations are not randomly recorded elves due to the fluctuation of the jet.

The averaged images illustrate that the average length of the jet decreases with increasing mixing ratio between $\frac{\dot{M}_{\text{MS}}}{\dot{M}_{\text{HS}}} = 0$ and $\frac{\dot{M}_{\text{MS}}}{\dot{M}_{\text{HS}}} = 10$. It should be stated that since $\dot{M}_{\text{HS}}$ remains constant at constant p_{inlet} , the total mass

Fig. 5 Influence of increasing mixing ratio on jet cavitation for $\beta = 0.075$ and $p_{\text{inlet}} = 100$ bar. The cavitating jet increases in length for increasing mixing ratio until a second area of cavitation is observed.

flow downstream the orifice $\dot{M}_{\text{total}}$ strongly increases with increasing mixing ratio. The instantaneous images also show in this context that single cavitation bubbles that are not dissolved after the orifice are carried out much faster with increasing mixing ratio. The trials do not allow determining whether the decreasing jet length is caused by a local pressure increase due to the insertion of the mixing stream or just a consequence of faster carrying out the cavitation bubbles. In either case, the reducing effect of the mixing ratio on the jet is limited, since the emergence of a second area of cavitation is observed at $\frac{\dot{M}_{\text{MS}}}{\dot{M}_{\text{HS}}} = 20$. This

effect can most likely be explained by the increase of flow velocity in the outlet channel due to the increase of $\dot{M}_{\text{total}}$. Those effects cannot be described in regard to σ since it does not consider the mixing stream.

The effect of the mixing ratio was also investigated at $p_{\text{inlet}} = 100$ bar and $\beta = 0.038$. The results are displayed in Fig. 6. In this case, both $\dot{M}_{\text{HS}}$ and $\dot{M}_{\text{total}}$ are equal to the flow rates at higher β , but due to the increased d_{outlet} , the average flow velocity in the outlet channel is much smaller.

Fig. 6 Influence of increasing mixing ratio on jet cavitation for $\beta = 0.038$ and $p_{\text{inlet}} = 100$ bar. The cavitating jet is not influenced by the increasing mixing ratio until a second area of cavitation is observed.

The images show that the effect of the increased mixing ratio proves to be much smaller than at $\beta = 0.078$. The length of the jet cavitation remains constant for mixing ratios up to 5 and is only visible at $\frac{\dot{M}_{MS}}{\dot{M}_{HS}} = 10$ if at all. For this reason, it can be concluded that the effect of the mixing stream comes into effect stronger when the jet cavitation is already confined by d_{outlet} . For $\frac{\dot{M}_{MS}}{\dot{M}_{HS}} = 17$, cavitation is also formed in the T-mixer and therefore, two cavitating jets collide where the mixing stream is inserted.

4.2.2 Influence of mixing ratio on σ_{ch}

With increasing p_{inlet} or decreasing σ , more cavitation bubbles are formed which extends the length of jet cavitation. At σ_{ch} , the single cavitation bubbles start to coalesce forming a cohesive vapor bubble. Figure 7 illustrates the influence of the mixing ratio on σ_{ch} . For trials at $\frac{\dot{M}_{MS}}{\dot{M}_{HS}} = 0$, the transition to choked cavitation was detected at $p_{inlet} = 450$ bar and $\sigma_{ch} = 0.0047$. During the recording of the image series, the cohesive bubble was periodically formed and carried out. As a result, the cohesive bubble is visible in some of the images (image Nr. 1), while some of the images show a jet consisting of single bubbles (image Nr. 2) as displayed in the top part of Fig. 7. In the averaged picture, this results in

a shadow right after the orifice outlet.

For $\frac{\dot{M}_{MS}}{\dot{M}_{HS}} = 1$, choked cavitation already occurs at p_{inlet}

$= 400$ bar and $\sigma_{ch} = 0.0053$. The shadow-graphic images in Fig. 7 do not indicate a further increase of σ_{ch} beyond doubt, while the averaged picture shows a hint of a cohesive vapor bubble just being formed at $p_{inlet} = 300$ bar. It is remarkable that the vapor bubble is always oriented to the bottom half of the OAMC. The reason for this could be small irregularities in the nozzle geometry due to its mechanical production. In literature, the transition of σ_{ch} was also observed for increasing β (Schlender et al., 2015b).

4.2.3 Influence of mixing ratio on hydraulic flip

Since the shadow-graphic images presented in the last section displayed that adding the mixing stream contributed to coalescence of the cavitation bubbles, this section deals with the question whether the mixing stream also affects the hydraulic flip. In Fig. 8, shadow-graphic images for $p_{inlet} = 150$ –250 bar and $\frac{\dot{M}_{MS}}{\dot{M}_{HS}} = 0$ and 1 are shown.

The images which were taken without adding a mixing stream for comparison purposes show jet cavitation for $p_{inlet} = 150$ bar. The cavitation pattern at $p_{inlet} = 200$ bar cannot be distinguished without doubt between jet cavitation and choked cavitation. At $p_{inlet} = 250$ bar and $\sigma_{ch} = 0.009$, the hydraulic flip has already occurred. Schlender et al. (2015b)

Fig. 7 Influence on mixing ratio on σ_{ch} for $\beta = 0.038$. The increase of the mixing ratio causes choked cavitation to occur at higher σ_{ch} .

Fig. 8 Influence of mixing stream on hydraulic flip at $\beta = 0.075$. The mixing stream provokes an hydraulic flip at lower p_{inlet} .

observed the occurrence of choked cavitation for $\beta = 0.075$ at $\sigma_{\text{ch}} = 0.0131$, which is in very good agreement to the results presented in this paper. The addition of the mixing stream at $\frac{\dot{M}_{\text{MS}}}{\dot{M}_{\text{HS}}} = 1$ causes the hydraulic flip to happen already at $p_{\text{inlet}} = 150$ bar. Since the outlet channel is completely filled with a cohesive vapor bubble, a further increase of p_{inlet} has no visible effects. Although the change in σ_{ch} could not be detected directly for the parameters examined, the results include the conclusion that σ_{ch} has also increased at $\beta = 0.075$.

For $\beta = 0.038$, a transition of the hydraulic flip to lower p_{inlet} could not be detected as shown in Fig. 9. In this case, the cavitation patterns are not affected by varying $\frac{\dot{M}_{\text{MS}}}{\dot{M}_{\text{HS}}}$ between 0 and 2. In conclusion, the results show that adding the mixing stream can promote the transition of jet cavitation to choked cavitation as well as the occurrence of the hydraulic flip. It therefore affects the cavitation patterns in a similar way as an increase of β . It is thus likely that the effect can be counteracted by decreasing β .

Since a further increase of $\frac{\dot{M}_{\text{MS}}}{\dot{M}_{\text{HS}}}$ leads to a reduction of jet cavitation for $\beta = 0.075$, shadow-graphic images were also taken at $\frac{\dot{M}_{\text{MS}}}{\dot{M}_{\text{HS}}} = 1, 2$, and $p_{\text{inlet}} = 200$ bar. The results in

Fig. 10 show that increasing the mixing stream leads to a shorter length of the outlet channel filled with the cohesive vapor bubble. Again, this effect could be ascribed to the fact that the cavitation bubbles are carried out faster.

Fig. 9 Influence of mixing stream on hydraulic flip at $\beta = 0.038$. The mixing stream does not influence the cavitation pattern in this case.

Fig. 10 Influence of mixing ratio on the cavitation pattern at $\beta = 0.075$ and $p_{\text{inlet}} = 200$ bar.

5 Conclusions

In this work we investigated the influence of a mixing stream on cavitation in the disruption unit of a high-pressure homogenizer. It was shown that the mixing stream does not change the Th numbers required to reduce cavitation by applying a back-pressure. Therefore, Th numbers found in literature for conventional high-pressure homogenization can be applied to SHM nozzles in order to suppress cavitation.

In addition, our investigations could show that increasing the mixing ratio of mixing stream to high-pressure stream can cause the cavitation bubbles in jet cavitation to coalesce at higher cavitation numbers σ and therefore increase σ_{ch} where choked cavitation is first observed. The increase of the mixing stream can therefore have a similar effect than an increase of the ratio β of outlet diameter to orifice diameter. In literature, hydraulic flip is described to be harmful for droplet breakup in HPH processes. Our results suggest that β should be adjusted to counteract the effect of the mixing stream. However, the increase of the outlet diameter could also change the mixing characteristics and thus influence droplet breakup. This should be further investigated in future.

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