Drop Break-up in High-Pressure Homogenisers

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ABSTRACT

The overall aim of this project was to investigate the drop break-up process in milk homogenisers. This was done by measurements and calculations of the flow fields in the gap region and by visualisation of drops being broken up.

To make visualisation and measurements possible, two scale models of a homogeniser gap were developed. The full-scale model was a direct copy of the gap in a production-scale homogeniser, but with optical access. Normal operational homogenisation pressures could be tested, and drops down to 5µm in diameter could be visualised. The second model was scaled-up about 100 times ensuring that the relevant dimensionless groups were kept constant, so that the same factors governed the drop break-up process. The scaled-up model was made of transparent plastic and was used for both velocity field measurements and drop visualisation. From these measurements it was concluded that the drops did not break up in the entrance of the gap. Larger drops were elongated to some extent and smaller ones remained spherical. Not much happens in the gap itself. The velocity profile is very flat throughout the gap in a production-scale homogeniser. In a pilot-scale homogeniser the boundary layers have time to grow and the velocity profile is almost developed at the gap exit. The growing shear layers seem to have a limited effect on the drops. During passage through the gap small drops will have time to relax back to their spherical shape, while large ones will leave the gap with almost the same aspect ratio as when they entered it.

This study shows that drop break-up takes place in the turbulent jet at the gap outlet. The flow velocity measurements show a very unsteady jet breaking down faster than a jet in a free liquid. Depending on the geometry of the chamber at the gap outlet, the jet can attach to either of the 45-degree walls and become a wall jet. The turbulence in the jet is very high, with turbulence intensities of 50-100%. Indications were found that flow structures of the size of, or slightly smaller than, the gap height, have very high intensities. Drop deformation experiments and theoretical analyses show that the eddies breaking up the drops range in size from much larger than, to just smaller than, the drop. The larger eddies deform the drop viscously by the velocity gradient created by the eddy. The smaller eddies deform the drop by fluid inertia.

The critical phase of the drop break-up process is the initial deformation. If the drop is deformed to an aspect ratio of 3-5, the drop is then very quickly elongated into one or more filaments which may be bent, coiled and further deformed before they break up into many small droplets.
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1. INTRODUCTION

In the dairy industry, as well as in many other processing industries, there is often a need to decrease the drop size in an emulsion. The reasons may be stability, mouth feel or reaction intensity. For the creation of sub-micron emulsions in low-viscous fluids the high-pressure homogeniser (HPH) has been found to be the most efficient machine (Karbstein [1], Walstra [2]).

A high-pressure homogeniser consists of a high-pressure piston pump and a narrow gap. The pump creates a pressure of 10 to 500 MPa, and in the gap the pressure is converted into velocity and the drops are broken up. For ease of manufacturing and to ensure high-pressure strength, the gap is annular in all production-scale homogenisers. Figure 1 shows the different parts of the gap in a pilot-scale homogeniser. The flow enters through the hole in the centre of the seat and is forced through the gap formed between the forcer and the seat. Note that the gap height is not fixed; the homogenisation pressure is controlled by the hydraulic actuator pushing the forcer against the seat. The gap height formed corresponds to the pressure loss of the liquid as it passes through the gap.

![Figure 1: The homogenisation device from a pilot-scale homogeniser: 1. forcer, 2. impact ring, 3. seat, 4. hydraulic actuator.](image)

In the gap the fluid is accelerated to up to hundreds of meters per second, and somewhere in the gap region the emulsion drops are broken up. Laboratory homogenisers sometimes have a circular orifice instead of an annular gap, and various authors have shown that these can be quite effective (Kolb [3], Dalgleish [4]). While this solution seems effective on a small scale, it is impossible to scale up to the production scale, as thousands of orifices would be required. A production-scale homogeniser can instead have more than one gap in parallel. Figure 2 shows a production-scale homogeniser gap where the gap height has been increased for the ease of visualisation.
The effectiveness of high-pressure milk homogenisers and their sensitivity to the input parameters have been investigated by various authors (Walstra [2], Kurzhals [5], Carter [6], Phipps [7], Kolb [8]). The main factor controlling the homogenisation effectiveness, i.e. the drop size, is of course the homogenisation pressure. The drop size is often described as a power function of the homogenisation pressure, as in Eq. 1

\[ d \propto P^q \]  

Eq. 1

Different investigators have found very different values of the exponent q. Walstra [2] states that it is -0.94 for a laboratory-scale and -0.61 for a production-scale homogeniser. Kurzhals [5] found it to be between -0.6 and -0.8, depending on gap geometry and second-stage pressure, while Carter [6] gives a value of -0.3 for a laboratory homogeniser. Phipps [7] presents a value of between -0.6 and -0.7 for moderate fat concentrations in a pilot-scale homogeniser and, finally, Kolb [8] found that for various round-orifice homogenisers the exponent have values between -0.2 and -0.4.

The second most important factor is the effect of the viscosity of the continuous and dispersed phases. Using the same type of power function Kolb [8] report that the exponent for the dispersed phase viscosity is between 0.2 and 0.4. Both Wang [9] and Kunio [10] found that above a certain viscosity threshold, the exponent was 0.75 and that it was close to zero when the viscosity of the dispersed phase is considerably lower than the threshold. Calabrese [11] argues from tank measurements that the exponent should be 1.67. Walstra [12] reports an exponent of 0.37 for both homogenisers and rotor-stator systems.

Tesch [13] showed that a lower continuous phase viscosity led to smaller drops in both a standard, annular gap and in a round orifice, but to larger drops in a Microfluidizer type homogeniser, were the gap consists of a very small orifice. Diels [14] used a homogeniser to kill bacterial cells and found greater efficiency with a lower continuous phase viscosity. Walstra [12] reported that in small homogenisers the drop size increased when the viscosity of the continuous phase was reduced, and the value of the exponent was -0.25.

As can be seen from the above there is absolutely no consensus on the effect of the parameters on the homogenisation efficiency. The experiments were performed on very different homogenisers, and the scatter in the experimental data indicates that there is
more than one break-up mechanism; and indeed, many different drop break-up mechanisms have been suggested. The most common ones are the planar shear, elongation shear, turbulent fluctuation and cavitation mechanisms. Walstra [2], Phipps [7], Stang [15], Mohr [16] and Bechtel [17], among others, have discussed the different mechanisms in detail, but there is no general consensus on which one dominates.

Most of the drop break-up theories are based on the relation between an external stress which deforms the drop, and the Laplace pressure, which tries to keep the drop spherical. When the external stress is based on inertial forces the relation between them is called the Weber number (We).

\[
We = \frac{\rho_e V^2}{\frac{2}{2\gamma} \frac{d \gamma}{4\gamma}} = \rho_e V^2 d
\]

Eq. 2

When the external stress is based on viscous forces the relation is called the capillary number (Ca).

\[
Ca = \frac{\eta \cdot G}{\frac{2\gamma}{2\gamma}} = \frac{\eta \cdot Gd}{2\gamma}
\]

Eq. 3

The above basic equations 2 and 3 can be extended by including, for example non-spherical drops and the deformation time.

To gain deeper knowledge of the drop break-up process it is necessary to study what exactly happens in the gap region in greater detail. One step on the way to understanding the drop break-up process is to visualise it. This has been done in scale models by, for example, Kolb [18] and Budde [19]. To scale a problem correctly it is necessary to have a theory describing the problem and then define the relevant dimensionless groups. If the theory describes the problem well, the results from a scaled experiment will agree with those from the original scale when the values of the dimensionless numbers are the same. The problem in drop break-up is that there is no commonly accepted theory on which to base the scaling.

Kolb [18] based his scaling only on geometrical similarity and the gap Reynolds number, while Budde [19] also included a generalised Weber number and the density and viscosity relations between the phases. Despite the differences in the methods of scaling they both observed the same qualitative drop deformation and break-up phenomena. Firstly the drops were elongated at the inlet of the gap. In Kolb’s study the drops were only slightly deformed, while in Budde’s the drops were elongated into long filaments. Secondly, in neither study did external forces affect the drops in the gap. Finally and most importantly, both studies showed that the drops are stretched, in Budde’s study more stretched, into long threads after leaving the gap. The threads are then further stretched and deformed by the
turbulence into irregular coils and “baskets”, which are finally broken up into many droplets, probably by a Raleigh mechanism.

Both Kolb and Budde’s studies show that 0.5-2.5 mm drops are broken up in the region after the gap. The question is whether the phenomena observed in their studies are also the same as in the case of micrometre drops in a milk homogeniser and what are the consequences on the validity of the different drop break-up theories.

Coalescence experiments performed for example by Floury [20], Lobo [21] and Walstra [22] report very low (<10%) coalescence during single-pass homogenisation. From this it can be concluded that, in a milk homogeniser, drop break-up is mainly a one-way process. The vast majority of the drops break up and remain broken up.
2. OBJECTIVES

In this study, both theory and experimental visualisation of the events at and around the homogeniser gap were employed. The focus was on the factors most relevant in a production-scale milk homogeniser. The drop break-up process was visualised in systems very similar to a commercial milk homogeniser. In a carefully scaled-up model the velocity fields in the gap region were measured and high-quality drop deformation and break-up images were obtained. The detailed drop deformation studies described in Paper 1 were preformed as in the early stages of this work it was believed that drop break-up took place at the gap inlet.

One factor believed to be important for the results of homogenisation is cavitation, i.e. the formation and implosion of bubbles in low-pressure regions, but this proved to be very difficult to visualise in the model equipment. The effect of cavitation was instead estimated based on measurements in a production-scale homogeniser.
3. **THE MILK HOMOGENISER**

In this study, the drop break-up process in the milk homogeniser was analysed using a commercial homogeniser, an extremely modified homogeniser, a scale model, and a four-roller mill. Milk homogenisers are available in very different sizes, from pilot-scale equipment with a capacity of 10 to 300 l/h, to production-scale machines with capacities of 10 000 l/h and above. The scale model developed here was compared with both a 120 l/h pilot-scale, and an 8 500 l/h production-scale homogeniser.

The milk homogeniser is run on 50°C milk with a density of $1.0 \cdot 10^3$ kg/m$^3$ and a viscosity of $8 \cdot 10^{-4}$ Pa s. The milk contains 0.5-4 % milk fat with a density of $0.9 \cdot 10^3$ kg/m$^3$ and a viscosity of $3.5 \cdot 10^{-2}$ Pa s in the form of fat droplets with diameters of 0.5-5 µm. During the homogenisation process the drops are broken down into droplets with diameters smaller than 1 µm. In this study, the original, large, 5 µm and the small 1 µm drops were used in the calculations. The surface tension of a natural milk drop is about 1.5 mN/m due to its lipid cover. In the homogenisation process the surface increases tenfold in much less than 1 ms. As the process is so fast, the newly created surfaces will have a surface tension close to that of the raw surface, namely 19 mN/m. In this study the value 19 mN/m was therefore used.

Both the pilot-scale and the production-scale homogenisers were run at a homogenisation pressure of 15 MPa and a Thoma number of 0.15 (defined as the pressure over the second stage relative to the total homogenisation pressure). Due to the fact that it is impossible to scale the diameter of the homogenisation device with the flow rate, the gap height is much higher in the production-scale homogeniser than in the pilot-scale homogeniser. It should be noted that the results of homogenisation are similar on the two scales. The details of the homogenisers are given in Table 1.
Table 1: Properties of a pilot- and a production-scale homogeniser.

<table>
<thead>
<tr>
<th></th>
<th>Pilot scale</th>
<th>Production-scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous phase viscosity</td>
<td>0.8 mPa s</td>
<td>0.8 mPa s</td>
</tr>
<tr>
<td>Continuous phase density</td>
<td>1000 kg/m³</td>
<td>1000 kg/m³</td>
</tr>
<tr>
<td>Dispersed phase viscosity</td>
<td>35 mPa s</td>
<td>35 mPa s</td>
</tr>
<tr>
<td>Dispersed phase density</td>
<td>700 kg/m³</td>
<td>700 kg/m³</td>
</tr>
<tr>
<td>Surface tension</td>
<td>19 mN/m</td>
<td>19 mN/m</td>
</tr>
<tr>
<td>Flow rate</td>
<td>0.12 m³/h</td>
<td>8.3 m³/h</td>
</tr>
<tr>
<td>Pressure</td>
<td>15 MPa</td>
<td>15 MPa</td>
</tr>
<tr>
<td>Gap width</td>
<td>3 mm</td>
<td>14 mm</td>
</tr>
<tr>
<td>Gap length</td>
<td>1 mm</td>
<td>1 mm</td>
</tr>
<tr>
<td>Gap height</td>
<td>15 µm</td>
<td>150 µm</td>
</tr>
<tr>
<td>Fluid velocity in the gap</td>
<td>115 m/s</td>
<td>175 m/s</td>
</tr>
</tbody>
</table>
4. MATERIALS AND METHODS

Four measurement systems were used in this study, each of which is described below.

4.1 Drop deformation measurement system

A four-roller mill (4RM) has been used to verify the elongation drop deformation model. A particle tracking method was used to measure the flow field velocity at the centre line of the four-roller mill. The drop deformation was measured using an image analysis method, the details of which are described in Paper 1.

Figure 3: Photograph of a 1.34 mm drop in the four-roller mill. The drop is being deformed in the elongation field in front of the two rollers. The flow is from left to right and the drop creating pipettes can be seen to the very left.
4.2 Full-scale visualisation system

A full-scale model of a high-pressure homogeniser (HPH) was used to visualise the drop deformation process at the gap inlet, in the gap, and at the gap outlet. The full-scale model consists of a cross-section of a production-scale homogeniser gap allowing it to be run at normal operating pressures and velocities (18 MPa and 100 m/s). Single-crystal sapphire windows allow optical access for a microscope, which together with a 20 ns pulsed laser system provided sharp images of moving drops down to 5 µm diameter. As the system had the same dimensions as a real homogeniser no scaling was necessary, but as it had to be run with drops about 5 times larger than those in a real homogeniser, the velocities were scaled with the square root of 5 to keep the drop size-to-dynamic pressure constant. The details and an analysis of the limitations of the system can be found in Paper 2.

![Figure 4: Photograph of the gap in the full-scale model, gap length 500 µm, gap height 400 µm.](image-url)
4.3 Scaled-up visualisation and flow measurement system

A scaled-up model of a high-pressure homogeniser was constructed in acrylic plastic with a scale factor of about 100. Great care was taken making sure the model was scaled properly, and that the dominating mechanisms in a real HPH were also dominating in the scale model. Firstly, the scale model was used to measure the flow field from the inlet to the outlet using particle image velocimetry (PIV) technology. The system was then run on water and the scaling was based on the Reynolds number and the ratio of the turbulence scale to gap height. The turbulent structures in the gap outlet region were analysed with a resolution of 0.5 mm or 1/10 gap heights. Proper orthogonal and Fourier decomposition were used to analyse the fluctuating structures. Secondly, the scale model was used to visualise the drop deformation and break-up process using drops between 0.25 and 1.5 mm in diameter. The system was scaled with respect to the Reynolds number, turbulence scale-to-gap height ratio, drop size-to-gap height ratio, drop size-to-turbulence scale ratio and drop Laplace pressure-to-deformation force ratio, by varying the gap height, velocity and fluid properties. The details can be found in Papers 3 and 4.
4.4 Production-scale homogeniser

A production-scale milk homogeniser (Alex 30, Tetra Pak, Lund, Sweden) with a capacity of 5 000 to 10 500 l/h was used for the cavitation analysis. The homogenisation device has a diameter of 30 mm. At full capacity and a homogenisation pressure of 20 MPa the gap height is about 170 µm and the gap velocity is 190 m/s.
5. THE GAP INLET

5.1 Gap inlet flow

The velocity field in the gap inlet region was measured and the elongation gradients calculated. A contour plot of the velocity can be seen in Figure 6. The fluid is flowing from left to right, and the fluid acceleration and the boundary layers can clearly be seen. The figure shows an average of 440 instantaneous velocity measurements. It can be seen that the velocities, and also the elongation, are slightly higher in the lower part, the inside of the curve. The unevenness of the contours and the strange wave form of the contours about 2 gap heights before the gap entrance is caused by the unevenness of the acrylic surfaces of the model. The windows were polished until they looked transparent but they were still quite uneven. As a result of this unevenness, the light was transmitted slightly differently from different positions, and the camera did not record the seeding particles in exactly the right positions. This resulted in an uneven and slightly noisy velocity field. Because of this, the elongation field could not be calculated as a numeric gradient of the velocity field, as the velocity was far too noisy, even with quite severe filtering. The elongation rates were instead calculated by fitting a power curve to the velocities along a few streamlines. The fitted curves were then differentiated to obtain the elongation rate.

The velocity at the very inlet of the gap and in the gap itself is not very accurate as there are too few interrogation areas to properly resolve the velocity profiles, but the acceleration seems to produce a quite flat velocity profile. The asymmetry in the inlet seems to give a small (10-20%) asymmetry in the gap velocity profile. This has also been verified by CFD calculations, by for example Karlsson [23]. The high inlet acceleration of course dampens out all turbulence.
Figure 6: Contour plot of the velocity field at the inlet of the gap. Dimensions given are gap heights. Elongation rate profile in Figure 7 (⋯). Flow is from left to right.

The maximum elongation rate varied from $150 \, s^{-1}$ at the top of the entrance of the gap to $220 \, s^{-1}$ at the bottom, corresponding to $0.4$ and $0.6$ times $U_0/h$. At a distance of two gap heights before the gap, the elongation rate was below $90 \, s^{-1}$, corresponding to $0.2 \cdot U_0/h$. The time the fluid spent in this high elongation rate region was about $0.05 \, s$, or roughly the inverse of the maximum elongation rate. The elongation rate along the dotted line in Figure 6 is shown in Figure 7.

Figure 7: Elongation rate profile along the dotted line in Figure 6
Based on the above found result that the maximum elongation rate at the gap inlet is $0.5 \cdot U_{0}/h$, the maximum elongation rate in full-scale homogenisers could be calculated. It was found that in a pilot-scale homogeniser the maximum elongation rate is $4 \cdot 10^{6} \text{ s}^{-1}$ and in a production-scale homogeniser $6 \cdot 10^{5} \text{ s}^{-1}$. 
5.2 Gap inlet drop deformation

5.2.1 Modelling drop deformation

A dynamic model was developed describing the deformation of a drop in an elongation field. The model is based on the pressure difference between the centre and the tip of an elliptic drop. The change in the deformation is then modelled as the difference between the effects of the elongation field and the surface tension on the drop.

\[
\frac{\partial L}{\partial t} = 2LG - \frac{2\gamma (L - B_d)}{\eta_c B_d}
\]

Eq. 4

In Eq. 4 above the effect of momentum transfer into the drop and inner circulation in the drop are not taken into account. This was done by introducing a parameter into Eq. 4 called the dynamic Weber number (\(\text{We}_d\)) thus creating the dynamic Weber number model.

\[
\frac{\partial L}{\partial t} = 2LG - \text{We}_d \frac{2\gamma (L - B_d)}{\eta_c B_d}
\]

Eq. 5

The details of the model can be found in Paper 1. The model was tested on aqueous drops in oil using a 4RM. The small-deformation theory developed by Taylor [24] predicts that with these fluids in the steady-state case with close to spherical drops, \(\text{We}_d\) should equal 0.5. Upon fitting the model to the data it was found that the agreement was excellent for the complete drop deformation process with a \(\text{We}_d\) of 0.42, as can be seen in Figure 8.
Figure 8: The aspect ratio of a drop simulated by the model compared with measurements. Dynamic Weber number model ( ), two series of measurements (□ and ◊), and elongation rate on the right y-axis as position reference (—).
The drop deformation at the gap inlet was also visualised in the full-scale model (see Figure 9).

Figure 9: Deformation of 5-50 µm drops at the gap inlet. Gap height 90 µm, gap velocity 70 m/s. The gap shape is indicated by white lines. Flow is from top to bottom.

As the value of the dynamic Weber number is not known for the viscosity ratio in a milk HPH, the model described in Paper 1 can not be used dynamically, but its steady-state solution can give some insight. Equation 5 with a $\text{We}_d$ of 0.42 was used to analyse the steady-state deformation of a drop, i.e. when the lengthening was zero. As the aspect ratio can not be derived from Eq. 5 analytically, the aspect ratio as a function of the capillary number was calculated numerically.
An equation was fitted to the numerical solution giving:

$$\mathcal{A} = \frac{12 \, Ca}{E^{-\frac{5}{3}} \, We_{c,t}}$$

Eq. 6

The validity of Eq. 6 was checked by observing the aspect ratio of the drops entering the gap for different drop sizes and elongation rates. The measurements agreed very well with the model, as can be seen in Figure 10. The theoretical model seems to hold very well until the drop is elongated so much it ceases to be elliptic. Visual inspection revealed that in a HPH this happens when the aspect ratio of in the order of 3.

![Figure 10: The drop deformation as a function of capillary number. The elongation rate is of the order of 10^5. Calculated from the model ( ). Experiment: 90 µm gap height ( ), 145 µm gap height ( ) and 220 µm gap height ( ).](image-url)
The elongation capillary numbers for the pilot-, production- and the full-scale model were calculated and can be found in Table 2.

Table 2: The elongation capillary number for the three scales.

<table>
<thead>
<tr>
<th></th>
<th>Pilot-scale</th>
<th>Production-scale</th>
<th>Full-scale model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large drops</td>
<td>0.40</td>
<td>0.06</td>
<td>0.15</td>
</tr>
<tr>
<td>Small drops</td>
<td>0.08</td>
<td>0.01</td>
<td>0.02</td>
</tr>
</tbody>
</table>

The elongation capillary numbers are quite low for all the systems. The results from the full-scale model can very probable be applied to the pilot- and production-scale homogenisers. The capillary number for the pilot-scale homogeniser is slightly higher, indicating that inlet deformation can be more important to the drop break-up process there. Stone [25] reported that an elongation capillary number of 0.12 is needed to break up a drop in the steady-state case, and the aspect ratio is then about 2. In a dynamic situation, as in the gap inlet, where the deformation time is very limited, the elongation capillary number must probably be higher.

5.2.2 Confined flow effects

When observing the drops entering the gap in the full-scale model it was noticed that most of them were elongated according to Equation 6, but that some of the larger drops became much more deformed, as can be seen in Figure 11. It seems that above a certain diameter the drops are affected by some other deformation mechanism.

Figure 11: The aspect ratio of drops entering the gap as a function of initial drop size. The elongation rate is of the order of $10^5$. Experiment: 90 µm gap height (♦), 145 µm gap height ( ), and 220 µm gap height ( ).
In Figure 12 two drops just inside the gap can be seen. The drop in Figure 12a has an initial diameter of 55 μm and is deformed to an aspect ratio of 3, while the drop in Figure 12b has an initial diameter of 60 μm and is deformed to an aspect ratio of 10.

Figure 12 a,b: The inlet elongation of drops at the gap inlet with initial diameters of a) 55 μm and b) 60 μm passing through a 90 μm gap. The mirror images on the left of each drop are reflections in the sapphire windows.

The difference seems to be that the larger drop is affected by the gap walls. It was found that when the drop was larger than about half the gap height, it started to interact with the walls. Then the continuous phase could not deform enough for the drop to retain its limited deformation, and instead the drop was squeezed through the gap resulting in a very large deformation.

It can thus be concluded, from both the visualisations and the theoretical discussion that the elongation velocity gradient at the gap inlet does not break up the drops. It elongates the largest drops, in the smaller machines quite substantially, but not sufficiently to break them. The small drops, those which are most difficult to break up, are hardly affected at all.
6. THE GAP

6.1 Gap flow

In a commercial homogeniser the gap height is unknown. The gap is closed with a screw or a hydraulic cylinder until the desired homogenisation pressure is obtained but the exact gap height is not known. The pressure, the velocity and the gap height were calculated using a one-dimensional model, taking friction and other losses into account. Figure 13 shows the distribution of the static pressure over the gap and, as can be seen, there is quite a large difference between the pilot- and production-scale homogenisers. The gap shape is included in the figure as a position reference. In the pilot-scale homogeniser the gap height is only 15 µm and most of the pressure is lost due to friction in the gap. In the production-scale homogeniser the gap height is 150 µm, the velocity is higher and most of the pressure is lost at the exit of the gap.

![Figure 13](image_url)

Figure 13: The relative pressure along a streamline through the gap in a pilot- and a production-scale homogeniser. The gap shape is given as a position reference. Pilot scale (····), production-scale (——) and gap shape (····).

It was not possible to measure the velocity profile in the gap as the resolution of the PIV measurements was not high enough. The velocity profile was instead calculated using boundary layer growth theory with the assumption that the velocity profile entering the gap is flat. In the gap the boundary layers start to grow and a more developed velocity profile will start to form. Schlichting [26] states that at the entrance of a channel the boundary layer growth of a flat plate can be used. The Reynolds number based on the boundary layer length will always be below $10^6$, thus the boundary layer is laminar. The displacement thickness normalized to the half-gap height is given by:
\[
\delta_1 \frac{h}{2} = 1.72 \sqrt{\frac{V \cdot x}{(\frac{h}{2})^2 U_0}}
\]

Eq. 7

This normalised displacement thickness at the exit of the gap is 60% for the pilot-scale and 5% for the production-scale homogenisers. The development of the velocity profile can also be described by the characteristic dimensionless inlet length:

\[
N_B = \frac{L \cdot V}{U_0 h^2}
\]

Eq. 8

If \(N_B\) is lower than \(3 \cdot 10^{-4}\) the flow is almost unaffected by passage through the gap and the boundary layers will have grown to less than 10% of the gap half-width. If \(N_B\) is higher than \(10^{-2}\) the boundary layers will merge and the velocity profile will be close to the steady-state profile. \(N_B\) for the pilot-scale homogenizer was \(3 \cdot 10^{-2}\) and the boundary layers have thus merged. In the production-scale homogeniser the boundary layers are very thin, \(N_B\) was \(2 \cdot 10^{-4}\) and it will take 130 gap lengths for the final velocity profile to develop. In both the velocity measurements and the drop images the flow in the gap seemed to be parallel and symmetric. There does not seem to be any major effect of the separation bubble thought to be present just downstream of the corner at the gap inlet. The 10-20% flow asymmetry in the gap predicted by the CFD runs [23] thus seems reasonable.

6.2 Gap drop deformation

6.2.1 Relaxation

The gap length in a real homogeniser is normally about 1 mm. With a velocity of over 100 m/s, it takes the drops less than 10 \(\mu s\) to pass through the gap. As the velocity profile is quite flat no external force acts on the drops during this period and the drops will start to relax back to spheres. The relaxation time from a deformation with an aspect ratio of 3, calculated using Eq. 5, is about 30 \(\mu s\) for a 5 \(\mu m\) drop and 6 \(\mu s\) for a 1 \(\mu m\) drop. The small drops will thus have time to relax, while the larger drops will still be deformed as they leave the gap.

6.2.2 Wall shear effects

Figure 14a shows the passage of 10-40 \(\mu m\) drops through a 220 \(\mu m\) gap in the full-scale model. The length of the gap is 1 mm and the fluid velocity is 50 m/s. The relaxation time for the 40 \(\mu m\) drops is greater than 100 \(\mu s\) so they do not have enough time to relax during the
passage through the gap. Figure 14b shows the growth of the boundary layers in the full-scale model and they reach only 13% of the gap width into the gap. As can be seen in Figure 14a the drops at the end of the gap are affected by the growing boundary layers and they start to rotate, but no other deformation can be observed.

Figure 14: a) The effect of the boundary layers on drops close to the gap wall. b) The growth of the boundary layers in the gap. Flow is from top to bottom. The mirror images on the left of each drop are reflections in the sapphire windows.

It can thus be concluded that the passage through the gap affects the drops very little. The velocity profile is flat, at least for the production-scale machines, and the shear layers seem to have very limited effect on the drops. The small drops will relax back to a spherical shape, if they were elongated at all at the inlet, while the larger, more deformed drops, will not have time for complete relaxation.
7. GAP EXIT

7.1 Gap exit flow

The velocity at the gap outlet and in the outlet chamber was measured with PIV using the scaled-up model. Due to the unevenness of the plastic surfaces the vector resolution was limited to 0.53 mm. As the Kolmogorov length scale is in the order of 0.02 mm, only the largest eddies could be resolved.

7.1.1 Jet direction

When the scaled-up model was first tested it was run with an asymmetric outlet, as in a commercial homogeniser. The jet formed at the outlet of the gap bent to the right, forming a large eddy in the exit chamber (see Figure 15). The eddy pushed the jet towards the wall and the jet became a wall jet after about 8 gap heights. The large eddy was very stable and no change in initial conditions could change the jet position.

Figure 15: Fluid velocity plot showing the bent jet in the asymmetric outlet chamber. Only part of the outlet chamber is shown. Dimensions in mm.

To test the effect of the outlet position on the jet, a dividing plate was mounted in the outlet chamber (indicated by the dashed line in Figure 5). It had a 50 x 80 mm hole centred on the right gap side, thus creating an almost symmetric exit chamber. With this symmetric outlet the exit flow became semi-stable. Depending on the conditions when the flow was started up, the jet either attached to the right wall, to the left wall, or became a straight jet. When the jet had chosen a direction it was stable and stayed there until the flow was stopped again. It was decided to continue the studies on the straight jet to allow comparison with results on straight jets in the literature. The straight jet can be seen in Figure 16. It can be seen here that considerable recirculation is created by the quite intense eddies stabilising the jet. This is the result of the confinement of the jet and cannot be seen in a free jet.
Figure 16: Fluid velocity plot showing the straight jet in the symmetric outlet chamber. Only part of the outlet chamber is shown. Dimensions in mm.

The jet was also observed in the full-scale model. The jet can be detected by the position of the drops as they leave the gap, as can be seen in Figure 17. As the left side of the gap continues after the gap the jet attaches to that wall.

Figure 17: Deformation and break-up of 5-50 µm drops. a) Gap outlet region, b) exit region 200-1400 µm downstream of the gap. Gap height 90 µm, gap velocity 70 m/s. The gap shape is indicated by white lines. Flow is from top to bottom.
7.1.2 Instantaneous flow field

The straight jet was then analysed further. Figure 18 shows four instantaneous images of the jet, and it can be seen that it is very turbulent and unstable. It moves from side to side and back and forth. The backflow region surrounding the jet shows large variations, with regions of liquid suddenly moving at high speed.

Figure 18: Four instantaneous images of the velocity field of a straight jet using a symmetric outlet. Dimensions in mm.
7.1.3 Jet spread

The average spread of the jet was calculated from 100 instantaneous velocity measurements. In Figure 19 the half-width of the jet is shown. The width of the jet is defined as the width where the velocity is half of the maximum velocity at that stream-wise position. The spread of the jet is then defined as Pope [27]

\[
S = \frac{dy_{(U/2)}}{dx}
\]

Eq. 9

If the spread is constant, this is an indication that the jet is self-similar. It can clearly be seen in Figure 19 that the jet has two self-similar regions. The jet behaves like a plane mixing layer from the gap to about 8 gap heights downstream. The spread in this region is about 0.07.

Figure 19: The spread of the jet defined as U/2. Measured data (---), fitted lines showing the two self-similar regions (—). Flow is from left to right.
Champagne [28] reports that the spread in plane mixing layers in different experiments is from 0.031 to 0.07, so the spread in the jet in the present study is high, but within the range of the literature data. After 8 gap heights the core of the jet disappears and the jet behaves like a self-similar plane jet. The spread is still quite constant, 0.14, which is also quite high compared with the value of 0.1 given by Pope [27] for a plane jet.

7.1.4 Jet movement

Figure 20 shows the positions of the maximum velocity for 100 instantaneous velocity fields, as grey to black dots. For each instantaneous velocity field, the local centreline of the jet was noted and its position was assigned a light grey colour; the more centrelines in the same position, the darker the dots. The width of the jet is also shown (black lines). As before, the width is defined as U/2, and it is centred on the average centreline. The most interesting information in Figure 20 is that it shows the magnitude of the jet’s large-scale motion. The motion of the jet is so large that the centreline often moves outside the U/2 lines.

![Figure 20](image)

Figure 20: The positions of the maximum velocity for 100 instantaneous velocity fields are shown as grey to black dots. The more centrelines in the same position the darker the dots. The width of the jet is also shown (heavy black lines).

7.1.5 Energy spectrum analysis

Proper orthogonal decomposition (POD) was applied to analyse the large structures of the velocity fluctuations. Mode energy is plotted versus mode number in Figure 21. The turbulent energy was normalised to the total energy to emphasize the relative energy content in the different modes.
It can be noted that only the first mode contains a significant amount of energy, and that the rest of the modes have a steadily declining and very low energy content, just as in a random signal. This means that, apart from some oscillation, there are no strong reoccurring structures, and that the jet fluctuates very randomly. The first mode containing a quite weak oscillation can be seen in Figure 22.
To analyse the small-scale structures of the velocity fluctuations a spatial Fourier spectrum was constructed. Figure 23 shows a spatial FFT spectrum constructed from velocity data collected along two horizontal lines within the jet, positioned 11 and 21 gap heights from the gap exit. The velocities along the lines from 100 instantaneous velocity fields were combined into two vectors, and the Fourier transforms of the vectors were analysed. A line with \(-5/3\) slope is included as a reference. The thin line shows the data from the area in the middle of the jet, 11 gap heights from the gap exit. The heavy line shows the data from the area at the top of the images, 21 gap heights from the gap exit. It can be seen that the turbulence energy is higher in the latter region, and the turbulence intensity was found to be 83\% in the second region, compared with 66\% in the first. It can also be noted that the smallest eddies observed with this measurement method (< 2 mm), seem to follow Kolmogorov’s \(-5/3\) law.

![Figure 23: Energy spectra of the turbulence at two positions in the jet region. Position 1, 11 gap heights from the gap exit (---). Position 2, 21 gap heights from the gap exit ( ). The -5/3 slope is included as a reference.](image)

7.1.6 Anisotropy

As the jet introduces considerable shear into the velocity field it is reasonable to assume that the turbulence of the larger scales is far from isotropic. Pope [27] states that for a turbulence field to be isotropic at a certain scale, the product of the shear and the eddy timescale at that length scale must be much smaller than 1.
\[ Sh \cdot \tau_{\text{eddy}} << 1 \]

Eq. 10

The shear is defined as \( U_0/h \) and the timescale in the inertial region as:

\[ \tau_{\text{eddy}}(l) = \frac{2}{3} \cdot \varepsilon^{\frac{1}{3}} \]

Eq. 11

where \( l \) is the eddy length scale. Using the energy density of \( 1/80 \cdot U_0^3/h \) from Eq. 15 gives:

\[ \frac{U_0}{h} \frac{2}{3} \frac{1}{80^3} \frac{1}{h^3} \ll 1 \Rightarrow l \ll \frac{h}{2.7} \Rightarrow l << 1.8\text{ mm} \]

Eq. 12

implying that eddies larger than 1.8 mm are affected by the shear fields and that the turbulence scales where the turbulence are isotropic is much smaller. This agrees very well with Figure 23 where the Kolmogorov -5/3 region seems to exist at length scales smaller than 1-2 mm. Note that in the scaled-up model drop deformation experiments, the Kolmogorov length scale was 25 µm, and the drop size 0.2 to 1.5 mm.

It can also be observed in Figure 23 that the turbulence energy of eddies a few times the drop size is very high, probably because of the shear, and it is quite likely that these eddies are important in the drop break-up process.

It can thus be concluded that the flow forms a jet at the gap exit. The jet can either be straight or attached to the walls, depending on the geometry of the outlet chamber. The limited dimensions of the outlet chamber create strong rotations that feed turbulence into the gap making the jet break up faster and more violent than most free jets described in the literature. The motion of the jet is very random with no recurring structures. The turbulence intensity in the gap is very high, with very high energy in fluid structures of the order of the gap height, while turbulent structures a few times smaller than the gap height seem to be isotropic and follow Kolmogorov’s -5/3 law.
7.2 Gap exit drop deformation theory

7.2.1 Turbulence length scales

Based on the findings in this work, but also on the findings of Walstra [2], Kolb [29], Mohr [16] and others, it appears that drop break-up takes place mainly in the jet created at the gap exit. The jet breaks down into turbulence eddies that break up the drops. To investigate the effect of the turbulence the intensity and the length scales of the turbulence structures must be calculated, and for this an estimate of the energy dissipation rate is needed.

The energy flux is given by:

\[ E = \frac{\rho_c U_0^2}{2} \cdot Q = \frac{\rho_c U_0^2}{2} \cdot U_0 \cdot h \cdot B_g \]  \hspace{1cm} \text{Eq. 13}

and the energy dissipation rate per unit mass is:

\[ \varepsilon = \frac{E}{V_{\text{dis}} \cdot \rho} = \frac{U_0^3 \cdot h \cdot B_g}{2 A_{\text{dis}} \cdot B_g} \]  \hspace{1cm} \text{Eq. 14}

Preliminary studies show that the flow in the gap continues as a jet after the gap exit. The kinetic energy in the jet is then converted into turbulence as the jet breaks down. These initial studies also showed that the jet has lost more than half of its velocity and thus most of its kinetic energy after a distance of 20 gap heights. The size of the high-turbulence region was estimated to be two gap heights high and 20 gap heights long in this study. The high-energy dissipation zone is of course concentrated to the outer, high-shear, regions of the jet and continues more than 20 gap heights, but 2 times 20 gap heights seem to be a good estimate of its size.
This gives:

\[
\varepsilon = \frac{U_0^3}{80h}
\]

Eq. 15

The Kolmogorov length scale can now be estimated, using:

\[
\eta = \left( \frac{v^3}{\varepsilon} \right)^{\frac{1}{4}}
\]

Eq. 16

The largest eddy scale is estimated to be:

\[
l_0 = \eta \cdot N_{Re_\theta}^\frac{3}{4}
\]

Eq. 17

With the above definitions, we obtain:

\[
l_0 = \eta \cdot N_{Re_\theta}^\frac{3}{4} = \left( \frac{v^3}{U_0^3} \right)^{\frac{1}{4}} \left( \frac{h \cdot U_0}{\nu} \right)^{\frac{3}{4}} \approx 3h
\]

Eq. 18

The data for the pilot- and production-scale homogenisers, and for the scaled-up model can be found in Table 3.
Table 3: Fluid data for the pilot- and production-scale homogenisers and for the scaled-up model.

<table>
<thead>
<tr>
<th></th>
<th>Pilot scale</th>
<th>Production scale</th>
<th>Scaled-up model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gap height</td>
<td>15 µm</td>
<td>150 µm</td>
<td>4.8 mm</td>
</tr>
<tr>
<td>Gap velocity</td>
<td>115 m/s</td>
<td>175 m/s</td>
<td>10 m/s</td>
</tr>
<tr>
<td>Energy dissipation rate</td>
<td>$1\cdot10^9$ m$^2$s$^{-3}$</td>
<td>$4\cdot10^8$ m$^2$s$^{-3}$</td>
<td>$3\cdot10^3$ m$^2$s$^{-3}$</td>
</tr>
<tr>
<td>Initial drop size</td>
<td>5 µm</td>
<td>5 µm</td>
<td>1000 µm</td>
</tr>
<tr>
<td>Final drop size</td>
<td>1 µm</td>
<td>1 µm</td>
<td>200 µm</td>
</tr>
<tr>
<td>Kolmogorov length scale</td>
<td>0.14 µm</td>
<td>0.18 µm</td>
<td>25 µm</td>
</tr>
<tr>
<td>Largest eddy</td>
<td>45 µm</td>
<td>450 µm</td>
<td>14 mm</td>
</tr>
<tr>
<td>Smallest eddy, inertial subrange</td>
<td>1.4 µm</td>
<td>1.8 µm</td>
<td>250 µm</td>
</tr>
<tr>
<td>Gap Reynolds number</td>
<td>2 200</td>
<td>33 000</td>
<td>4 800</td>
</tr>
</tbody>
</table>

It seems very plausible that the key process is the initial deformation of the spherical drop. The Laplace pressure is greatest for spherical drops, and their round shape makes the drops difficult to deform. When the drop is deformed to an aspect ratio of 3 or more, the Laplace pressure decreases and the drop becomes longer, making further deformation and break-up much easier. Therefore a spherical drop is used in the drop break-up calculations.

7.2.2 Basic drop break-up mechanisms

Walstra [2] defines two major turbulent drop break-up mechanisms: the turbulent viscous (TV) and the turbulent inertial (TI) mechanism. In the turbulent viscous mechanism the drops are smaller than the eddies and are subject to the viscous stresses caused by the strong velocity gradients created by the turbulent eddies. In the turbulent inertial mechanism the drops are generally larger than the eddies and are subject to the inertial pressure fluctuations caused by the rapid velocity changes created by the turbulent eddies.
In the TV mechanism it is the velocity gradient that affects the drops. According to Kolmogorov’s theory for the inertial subrange, the velocity gradient of an eddy of size $l$, is:

$$G(l) = \frac{\varepsilon^{2/3}}{l^{5/3}}$$

Eq. 19

Thus the viscous stress on the drop can be estimated by using the relation:

$$\sigma = \eta_c \varepsilon^{2/3} l^{2/3}$$

Eq. 20

From this it can be concluded that, to deform a drop of a certain size, the smaller the eddy, the greater the stress, and the most effective eddy is an eddy of almost the same size as the drop. Remember that a prerequisite for the TV mechanism was that the eddy is larger than the drop.

In the TI mechanism the inertial forces will cause the break-up of the drop. The eddy velocity in the inertial subrange, for eddies of size $l$, can be estimated as:

$$u(l) = (\varepsilon l)^{1/3}$$

Eq. 21

giving an eddy dynamic pressure estimate of:

$$P = \frac{\rho_c (u(l))^2}{2} = \frac{\rho_c (\varepsilon l)^{2}}{2} = \frac{\rho_c \varepsilon^{2/3} l^{2/3}}{2}$$

Eq. 22

From this it can be concluded that, to deform a drop of a certain size, the larger the eddy, the greater the stress, and the most effective eddy is an eddy of almost the same size as the drop. Remember that a prerequisite for the TI mechanism was that the eddy is of the same size or smaller than the drop.

Walstra [2] and Mohr [16] defined the boundary between the TV and the TI regions as when the drop Reynolds number
\[ \text{Re}_d = \frac{u \cdot d \cdot \rho_c}{\eta_c} \]  
Eq. 23

is equal to unity. Using Eq 21 for the velocity and assuming an eddy of the same size as the drop, this gives:

\[ \text{Re}_d = 1 = \left( \frac{(\varepsilon d)^{\frac{1}{3}}}{\nu_c} \right) d = \left( \frac{(\varepsilon d)^{\frac{4}{3}}}{\nu_c} \right) \]  
Eq. 24

which results in:

\[ d = \left( \frac{\nu^3}{\varepsilon} \right)^{\frac{1}{2}} = \eta \]  
Eq. 25

So, with these definitions, that the drop Reynolds number is equal to unity, is the same as the drop size being equal to the Kolmogorov length scale.

Defining the boundary between the regions in terms of the Kolmogorov length scale may seem a little strange. Drops larger than the Kolmogorov length scale could be affected by larger eddies arising from the TV mechanism, as described above. In this study, the following distinction is proposed for the active break-up mechanism: If the effective eddies breaking up the drops are larger than the drops, then the TV mechanism is responsible, and if they are smaller, then the TI mechanism is involved.

Careful studies of the high-wavenumber part of any turbulence spectrum, for example in Pope [27], page 235, show that the intensity of the eddies at the Kolmogorov scale are much lower than the intensity predicted by the $k^{-5/3}$ law in the inertial subrange. As can be seen in Table 4 the eddies must be about 10 times the Kolmogorov length scale to achieve the inertial subrange intensities. Thus, if the energy in the system is just sufficient to break the drops, the smallest eddy capable of breaking a drop is probably 10 times larger than the Kolmogorov length scale. As can be seen in Table 3, the size of these eddies is smaller than the initial drop but larger than the final drops. It can thus be concluded that inertial effects can break up the initial drops, but viscous effects are important in breaking up all drops into the final drop size.

<table>
<thead>
<tr>
<th>Eddy size</th>
<th>Relative energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1 \times \eta$</td>
<td>$&lt;1%$</td>
</tr>
</tbody>
</table>
2 x η | 10%
---|---
5 x η | 50%
10 x η | 100%

7.2.3 Eddy based drop break-up theory

From the break-up mechanisms described above, one may define the eddy-based turbulent capillary number and Weber number. These definitions are based on the assumption that the eddy and droplet sizes are similar. Also, in the former case, it is assumed that the velocity gradient scale is similar to the droplet size, and in the latter case that the droplet slip velocity is of the same order as the eddy velocity. These assumptions are not unreasonable since it was found above, in both mechanisms, that the most effective eddy in breaking up a drop is an eddy of the same size as the drop. Therefore, an eddy of the same size as the drop is used in the capillary and Weber number definitions.
In the TV region:

\[ Ca_{TV} = \frac{\eta \varepsilon^2 d^\frac{2}{3} d}{2\gamma} = \frac{\eta \varepsilon^3 d^\frac{1}{3}}{2\gamma} \quad \text{Eq. 26} \]

and in the TI region:

\[ We_{TI} = \frac{\rho v^2 d^\frac{2}{3} d}{2\gamma} = \frac{\rho \varepsilon^5 d^\frac{5}{3}}{4\gamma} \quad \text{Eq. 27} \]

The capillary and Weber numbers for the two mechanisms, and the initial and final drop size can be found in Table 5, where it can be observed that the TI break-up mechanism seems to be very effective on large drops and much less effective on small drops. The TV capillary number is low in all cases but varies very little with drop size. As noted before, in a steady state system a capillary number of 0.12 is sufficient to break up a drop.

Table 5: Drop break-up numbers for the three different scales.

<table>
<thead>
<tr>
<th></th>
<th>Pilot scale</th>
<th>Production scale</th>
<th>Scale model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca_{TV}, initial drop</td>
<td>0.4</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Ca_{TV}, final drop</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>We_{TI}, initial drop</td>
<td>23</td>
<td>11</td>
<td>19</td>
</tr>
<tr>
<td>We_{TI}, final drop</td>
<td>1.5</td>
<td>0.8</td>
<td>1.3</td>
</tr>
<tr>
<td>T_{TI}, initial drop</td>
<td>2.6</td>
<td>1.9</td>
<td>34</td>
</tr>
<tr>
<td>T_{TI}, final drop</td>
<td>0.3</td>
<td>0.2</td>
<td>4</td>
</tr>
</tbody>
</table>
7.2.4 Stokes number

Equation 27 above is valid only if the drop does not follow the eddy. This will happen when the Stokes number, St, is large (St>> 1). The Stokes number is defined as the ratio of particle adjustment time to the flow and the timescale of the flow or the eddy:

$$ St = \frac{\tau_{\text{particle}}}{\tau_{\text{eddy}}} $$

Eq. 28

If St << 1 the drop follows the flow, and if St >> 1 the flow fluctuates around the drop and the slip velocity can be approximated by the flow velocity. The drop response time in Stokes flow is defined as:

$$ \tau_{\text{particle}} = \frac{\rho_d d^2}{18 \eta_c} $$

Eq. 29

Defining the eddy timescale in the inertial region as the inverse of the gradient in Eq. 19 gives:

$$ St = \frac{\tau_{\text{particle}}}{\tau_{\text{eddy}}} = \frac{\rho_d d^2}{18 \eta_c} \frac{d^2 l^{-\frac{2}{3}} \cdot \varepsilon^{-\frac{1}{3}} \rho_d}{18 \eta_c} $$

Eq. 30

The values of the Stokes number for different drop and eddy sizes for a production-scale homogeniser, are shown in Figure 24, where it can be seen that only the largest drops are affected by the inertial effects of the eddies. Thus, the smaller drops follow the eddies and are not deformed by the eddy inertia.
In the TV mechanism the drops are smaller than the eddy causing the velocity gradient, always giving a low Stokes number, but as the break-up mechanism is viscous it is relatively insensitive to the Stokes number.

7.2.5 Deformation time

The lifetime of an eddy is quite short, and an eddy may not exist long enough to break up the drop. The drop deformation time can be defined as the drop’s viscosity divided by the stress acting on the drop (Walstra [2]).

\[ \tau_{\text{def}} = \frac{\eta_d}{\sigma} \]

Eq. 31
The dimensionless time, defined as the eddy timescale normalised to the drop deformation
time, determines whether the eddy exists long enough to break up the drop or not. If the
normalised time is $> 1$, the eddy lifetime will not effect the break-up, but if it is $< 1$ the drop
break-up will very likely be limited by the short lifetime of the eddy. The expressions of
this time relation for the two mechanisms are:

$$T_{TV} = \frac{\tau_{eddy}}{\tau_{def TV}} = \frac{\left(\frac{l^2}{\varepsilon}\right)^{\frac{1}{3}}}{\eta_d^{\frac{1}{2}} \eta_d^{\frac{2}{3}}} = \frac{\eta_c}{\eta_d}$$

Eq. 32

and

$$T_{TI} = \frac{\tau_{eddy}}{\tau_{def TI}} = \frac{\left(\frac{l^2}{\varepsilon}\right)^{\frac{1}{3}}}{\rho_c^{\frac{1}{2}} \eta_d^{\frac{2}{3}}} = \frac{\rho_c}{\eta_d}$$

Eq. 33

In the TV mechanism the time relation breaks down to the inverse of the viscosity ratio,
giving the value of 0.02 in a milk homogeniser, indicating that the TV mechanism is limited
by not having sufficient time to break up the drops. The time relation for the TI mechanism
can be found in Table 5 on page 45. For large drops there seems to be sufficient time for
break-up but for small drops the time is rather short. It should be noted that the value of this
time ratio is much higher in the scale model indicating that the TI mechanism may be more
effective there than in the pilot- and production-scale homogenisers.
7.2.6 Turbulent drop break-up summary

The theoretical discussion above is summarised in Table 6 in terms of the different mechanisms and the most relevant dimensionless numbers. The TI mechanism seems to be the more effective one for the break-up of the initial drop, with both a high Weber number and sufficiently long break-up time. Its efficiency decreases for the much smaller final drop, especially since eddies smaller than the final drop approach the Kolmogorov length scale and have very low energy content. The TV mechanism seems to be much less effective, but its efficiency is reasonably constant for the initial and final drops. As could be seen in Figure 23 the turbulence spectra of the scale model show that at scales comparable to the gap height, the eddies have a very high energy content. This may increase the effectiveness of the TV mechanism, especially in the pilot-scale homogeniser, where the gap is only 15 µm high.

<table>
<thead>
<tr>
<th></th>
<th>TV initial drop</th>
<th>TV final drop</th>
<th>TI initial drop</th>
<th>TI final drop</th>
</tr>
</thead>
<tbody>
<tr>
<td>We/Ca</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>Stokes number</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>Time to deform</td>
<td>Very low</td>
<td>Very low</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>
7.3 Gap exit drop experiments

In Figure 25 the drop break up process in the full-scale model can be seen. Note that the same drop was not photographed four times, instead four similar drops were photographed in different positions. The initial drop diameter was about 400 µm. The gap was 400 µm long and 370 µm high. The velocity of the continuous phase was 8 m/s giving a gap Reynolds number of $3 \cdot 10^3$. A mixture of fairly round drops and filaments is flowing into the gap. The drops are elongated at the entrance of the gap (Figure 25a), and at the exit the flow forms into a jet. When the drops reach the large recirculation loop in the exit region they start to deform (Figure 25b). As the drops move further downstream with the jet, they are further deformed and finally break up into many small droplets in the intensely turbulent region created by the breakdown of the jet (Figure 25c,d).

Figure 25 a-d: Deformation and break-up of 400 µm drops. Gap height = 370 µm, gap velocity = 8 m/s. a) Gap inlet region, b) gap outlet region, c) and d) exit region 800-2000 µm downstream of the gap).

Figure 26 a,b shows the break-up of smaller drops in the full-scale model. Drops with 5-50 µm diameter were released from a capillary shown at the top of the image in Figure 9. They were deformed in the elongation field at the inlet of the gap. The average flow velocity of the continuous phase was about 70 m/s and the gap height was 90 µm. The gap Reynolds number was $6 \cdot 10^3$ and the maximum elongation rate at the inlet of the gap was $8 \cdot 10^5$ s$^{-1}$. In Figure 26a it can be seen that the majority of the drops travel almost straight down. Most of the drops are totally enclosed in the jet and they are only rotated slightly by the deceleration of the right-hand part of the jet. In Figure 26b the jet still travels straight down. Only in the lower part of Figure 26b does the jet start to break down and the drops are deformed. As the jet is a wall jet it starts to break down on the right-hand “free” side. The drops located in the “free” region are affected earlier by the intense shear and turbulence created by the jet breakdown. About 1200 µm downstream of the gap the jet has almost totally broken down
into a very intense turbulent field. The drops caught in the eddies are deformed and broken up into small droplets.

Figure 26: Deformation and break-up of 5-50 µm drops. Gap height = 90 µm, gap velocity = 70 m/s. a) Gap outlet region, b) exit region, 200-1400 µm downstream of the gap. The gap is indicated by white lines.

Figure 27 shows two typical images from the scaled-up model, taken 1 ms apart when oil was injected through a needle in front of the gap. In these images the oil flow rate was high enough for a combination of drops and filaments to form. The drops created in this system had diameters of 0.2 to 1.5 mm. The drops and filaments passed the gap largely unaffected and continued into the jet formed at the gap exit. When the jet broke down, the drops and filaments were deformed and broken up. The jet is the area free from broken-up drops that fills the circulation regions on both sides of the jet.
Figure 27: Example of a double image of a filament being broken up by the jet. Dimensions in mm and 1 ms separation time between the images.
To visualise the break-up process the double-image capability of the PIV system was utilized. The separation time between the images was always 1 ms. Figure 27 covers only the region from 1 to 7 gap heights from the gap exit. The motion and diameters of the eddies can be seen in the centre of the images. The filament is swirled around in the upper part of the images, and in the lower part the break-up of the drops and filaments can be seen. It should be noted that the most effective drop break-up region is 50 to 100 mm further downstream of the gap.

As the smallest possible interrogation area with the scaled-up system is about 0.5 mm, it is impossible to accurately measure the flow around a drop smaller than 2 mm. Instead, the size of the turbulent structures, or eddies, deforming and breaking the drops was estimated based on the shape of the drops themselves. If the drop deformation is regular and the whole drop is deformed in the same qualitative way, it can be concluded that the flow structure deforming the drop was larger than the drop, and that the TV mechanism is responsible for the deformation. If the drop is unevenly deformed it can be concluded that the structure deforming the drop was of the same size as or smaller than the drop, and that the TI mechanism is responsible for the deformation.
Figure 28 shows five pairs of drops with original diameters of 0.3 to 1.2 mm. During the 1 ms between the first and the second image the drops were mainly deformed by large flow structures. During or after the large-scale deformation, the drops are often further deformed by smaller flow structures, seen as bending of the drawn-out drop. This effect is very prominent in the last pair of drops in Figure 28. The fact that no drops have a purely elliptical shape indicates that the break-up mechanism is of both TV and TI character, i.e. superimposed on the strong TV mechanism there is always a TI mechanism.

![Figure 28](image1)

Figure 28: Drops deformed by flow structures larger than the drop. Undeformed drops are shown in the upper row and deformed drops 1 ms later in the lower row.

Figure 29 shows five pairs of drops deformed by small flow structures. The drops are deformed irregularly and in some images only part of the drop is deformed. The flow structures deforming the drops are of the same size or smaller than the drops. The smallest inertial subrange eddy was calculated and found to be 0.25 mm and, out of hundreds of images analysed, in no case was a drop deformed or broken up by an eddy smaller than that.

![Figure 29](image2)

Figure 29: Drops deformed by flow structures of the same scale as or smaller than the drop. Undeformed drops are shown in the upper row and deformed drops 1 ms later in the lower row.
Figure 30 shows more severely deformed drops during the 1 ms between the images. The maximum deformation is about 4 mm, giving a velocity of 4 m/s. As the inertial subrange eddy velocity of a 1 mm eddy was calculated to be about 1 m/s, this indicates that a larger eddy has affected the drops.

Figure 30: Drops extremely deformed during the 1 ms between the images. Undeformed drops are shown in the upper row and deformed drops 1 ms later in the lower row.

Figure 31 shows three slightly larger drops being deformed by mostly larger flow structures. The fact that these fairly large drops are deformed by even larger structures strengthens our hypothesis that the TV mechanism can be effective on drops very much larger than the Kolmogorov length scale. This result agrees very well with the spectra in Figure 23 where an unexpected intensity increase was found for eddies larger than 2 mm, probably due to the high anisotropic shear caused by the jet.

Figure 31: Larger drops deformed by flow structures much larger than the drop. Undeformed drops are shown in the upper row and deformed drops 1 ms later in the lower row.
Figure 32 shows three drops in the later stages of break-up where the whole break-up process can be observed. The experiments showed that the critical phase in the break-up process is the initial deformation. When the drop has been sufficiently deformed by an intense enough eddy, large or small, the other eddies always present around it can easily deform it further. The drop is then drawn out into a filament or a number of filaments that are then further drawn out, coiled and finally disintegrated into small drops. In very few instances did a deformed drop relax back to its original spherical shape, but it was not uncommon that only part of the drop was drawn out into a filament while the rest of the drop relaxed back into a sphere. The random nature of the turbulence was exemplified by the fact that some drops travelled far before breaking up while others broke up close to the gap exit.
It can thus be concluded that there are two major turbulent break-up mechanisms: the turbulent viscous and the turbulent inertial. In the turbulent viscous mechanism the eddies are generally larger than the drop and in the turbulent inertial mechanism they are generally smaller. The theory indicates that the turbulent inertial mechanism is more effective in breaking down large drops while the turbulent viscous mechanism has almost the same efficiency on both large and small drops. It should be noted that the smallest drops broken up in a homogeniser are about five times the Kolmogorov length scale, and eddies smaller than these drops have a very low energy content.

From the drop deformation and break-up images it can be concluded that eddies of sizes from slightly smaller than, up to much larger than, the drops are responsible for drop break-up, indicating that both the above discussed mechanisms are simultaneously in effect.
8. CAVITATION AND 2nd STAGE EFFECTS

Some authors, among them Mohr [30], Kurzhals [31] and Loo [32], have argued for the importance of cavitation. Mohr [30] and Kurzhals [31] showed that homogenisation is most efficient if the second-stage pressure is between 15 and 20% of the homogenisation pressure. Kurzhals also found a maximum in the ultrasound intensity, expected to originate from cavitation, at the same pressures. Using an older homogeniser with a long gap Loo [32] showed that the most effective homogenisation was obtained without any second-stage pressure. However, at dairies using modern production-scale milk homogenisers it is a proven fact that the most efficient homogenisation is achieved with a second stage pressure of 15-20% of the homogenisation pressure.

8.1 Gap height measurements

Kurzhals [31], among others, has proved beyond any doubt that a production-scale milk homogeniser without second-stage pressure cavitates. As cavitation is a complex phenomenon it is very difficult to calculate the maximum second-stage pressure at which the first stage cavitates. However, if there is excessive cavitation in the gap, the bubbles will take up a great deal of volume forcing the gap to open up more. To analyse the regions of cavitation, the gap height in a production-scale milk homogeniser was measured. The gap was fitted with a laser measuring system (LB-72W, Keyence Corp. Osaka, Japan) detecting the position of the forcer. The stress on the gap structure is very high when running at high pressures and the deformation of the structure is at the same order of magnitude as the gap height. Therefore, readings of the laser measurements were compensated for the calculated structural deformation. The measured gap height as a function of the pressure over the first homogeniser gap can be seen in Figure 33. The gap height calculated using the one-dimensional model described in the section on gap flow is shown as a dotted line. The measurements were run with homogenisation pressures of 10, 15, 20, 25 and 30 MPa and second stage pressures of 0, 2, 4, 6 and 8 MPa. Figure 33 show five curves, one for each homogenisation pressure. Each curve has five points, one for each second-stage pressure. The pressure over the first gap is simply the difference between the homogenisation and the second-stage pressures. In the figure it can be seen that most of the points fall on one line, but that some points show a higher gap opening than expected. Careful inspection revealed that these higher gap openings were found when the second-stage pressure was low, i.e. when the gap is likely to cavitate.
Figure 33: Gap height as a function of the pressure over the first gap. Homogenisation pressures: ♦ 10 MPa, 15 MPa, 20 MPa, • 25 Mpa and ◊ 30 Mpa.

A summary of the pressure of the second stage relative to the homogenisation pressure can be found in Table 7. The pressure combinations with higher gap openings, i.e. where cavitation is expected are shown in boldface.

Table 7: Ratio of second-stage pressure to homogenisation pressure in a production-scale milk homogeniser. Cavitating combinations are shown in boldface.

<table>
<thead>
<tr>
<th>Homogenisation pressure</th>
<th>2nd stage pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 MPa</td>
</tr>
<tr>
<td>10 MPa</td>
<td>0%</td>
</tr>
<tr>
<td>15 MPa</td>
<td>0%</td>
</tr>
<tr>
<td>20 MPa</td>
<td>0%</td>
</tr>
<tr>
<td>25 MPa</td>
<td>0%</td>
</tr>
<tr>
<td>30 MPa</td>
<td>0%</td>
</tr>
</tbody>
</table>
It seems as the 15-20% second stage pressure, found to give the most effective homogenisation, is sufficient to eliminate the excessive cavitation that leads to a large volume of bubbles causing increased gap openings.

8.2 Wear measurements

To find other indications of the existence of cavitation the wear on a homogenisation device was analysed. A new device was mounted in the first stage in the production-scale homogeniser and it was run on water at a homogenisation pressure of 40 MPa and a second-stage pressure of 8 MPa for almost 1000 hours. The seat and forcer were made in Stellite 20, a special wear-resistant alloy with a DPH hardness of over 600. The wear on the gap was then measured with a skid less stylus instrument (Surfascan 3CS, Somiconic, France) along four radial lines at 90° to each other. The wear pattern was very symmetric around the gap, with two distinct wear regions (Figure 34). One region was found at the corner of the entrance of the gap. In this region a separation bubble is likely to form and the pressure will be very low with a high likelihood of cavitation. The other region was found on the other side of the gap about 700 μm downstream of the entrance.
Note that the wear and the gap height are to scale in the figure and that the wear is greater than the gap height. The sharpness and deepness of the wear at the second position and the fact that the gap exit shows no wear at all can only be explained by cavitation wear, while the exact mechanism behind this effect is unknown.

Figure 34: Wear of a homogeniser gap after running on water for 1000 hours at 40 MPa. Dimensions in µm. Flow is from left to right. The straight lines indicate the original gap shape.

It can thus be concluded, both from the literature, and from experience using commercial homogenisers, that the second stage is important and the optimum second-stage pressure is in the range of 15-20% of the homogenisation pressure. It appears that a second-stage pressure of this order of magnitude eliminates the main volume of the cavitation bubbles, but both the ultrasound intensity and the wear pattern indicate that cavitation is still present.

9. CONCLUSIONS

By combining the findings in this study with other researchers’ results it is now possible to form a fairly coherent picture of what happens as a drop passes through a high-pressure homogeniser. From both the theoretical and the experimental analyses it can be concluded that the drops do not break up at the gap inlet. The elongation field is only strong enough for the larger drops to be deformed and stretched out to an aspect ration of 3-5, while the small drops remain almost spherical.

Little seems to happen actually in the gap. There does not seem to be any major effect of the separation bubble thought to be present just downstream of the corner at the gap inlet. The velocity profile is quite flat throughout the gap in the production-scale homogeniser. In a small pilot-scale homogeniser the boundary layers have time to grow and the velocity profile is almost fully developed at the gap exit. The growing shear layers seem to have limited effect on the droplets. During passage through the gap the small drops will have time
to relax back to their spherical shape, while the large ones will leave the gap with almost the same aspect ratio as when they entered it.

This study shows that drop break-up takes place in the turbulent jet at the gap outlet. The flow velocity measurements show a very unsteady jet breaking down faster than a jet in a free liquid. Depending on the geometry of the chamber at the gap outlet the jet can attach to either of the 45-degree walls and become a wall jet. The turbulence in the jet is very high, with turbulent intensities of 50-100%. There is an indication that flow structures of the size of, or slightly smaller than, the gap height, have very high intensities. Drop deformation experiments and theoretical analyses show that the eddies breaking up the drops range from much larger than, to just smaller than, the drop. The larger eddies deform the drop viscously by the velocity gradient created by the eddy. The smaller eddies deform the drop by fluid inertia.

The critical phase of the drop break-up process is the initial deformation. If the drop is deformed to an aspect ratio of more than 3-5, it is then very quickly elongated into one or more filaments that are bent, coiled, and further deformed before it break up into many small droplets.
In a milk homogeniser drop break-up is mainly a one-way process. The vast majority of the drops break up and remain broken up. This means that, in milk homogenisation, the final drop size depends only on the break-up power of the turbulence and not on the coalescence rate.

The effect of cavitation and the second-stage pressure remain unknown. Either cavitation has no effect and the only role of the second stage is to break up agglomerates formed after the first stage, or the second stage adjusts the cavitation, keeping the cavitation bubbles small and making then implode at the right instance maximising their drop disruption effect.
## NOTATIONS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-</td>
<td>Aspect ratio, L/B of the deformed drop</td>
</tr>
<tr>
<td>$A_{\text{diss}}$</td>
<td>m²</td>
<td>Energy dissipation area</td>
</tr>
<tr>
<td>$B_d$</td>
<td>m</td>
<td>Smallest diameter of the deformed drop</td>
</tr>
<tr>
<td>$B_g$</td>
<td>m</td>
<td>Gap width</td>
</tr>
<tr>
<td>$Ca$</td>
<td>-</td>
<td>Capillary number</td>
</tr>
<tr>
<td>$Ca_{\text{TV}}$</td>
<td>-</td>
<td>Viscous eddy capillary number</td>
</tr>
<tr>
<td>$d$</td>
<td>m</td>
<td>Drop diameter</td>
</tr>
<tr>
<td>$E$</td>
<td>Nms⁻¹</td>
<td>Energy flux</td>
</tr>
<tr>
<td>$G$</td>
<td>s⁻¹</td>
<td>Velocity gradient</td>
</tr>
<tr>
<td>$h$</td>
<td>m</td>
<td>Gap height</td>
</tr>
<tr>
<td>$I$</td>
<td>m</td>
<td>Eddy length in the inertial region</td>
</tr>
<tr>
<td>$I_0$</td>
<td>m</td>
<td>Largest eddy</td>
</tr>
<tr>
<td>$L$</td>
<td>m</td>
<td>Drop length</td>
</tr>
<tr>
<td>$N_B$</td>
<td>-</td>
<td>Dimensionless boundary layer length</td>
</tr>
<tr>
<td>$N_{\text{Re}}$</td>
<td>-</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>$P$</td>
<td>N</td>
<td>Dynamic pressure</td>
</tr>
<tr>
<td>$Q$</td>
<td>m³s⁻¹</td>
<td>Total flow rate</td>
</tr>
<tr>
<td>$q$</td>
<td>-</td>
<td>Pressure exponent</td>
</tr>
<tr>
<td>$Re_d$</td>
<td>-</td>
<td>Drop Reynolds number</td>
</tr>
<tr>
<td>$S$</td>
<td>-</td>
<td>The spread of the jet based on U/2</td>
</tr>
<tr>
<td>$Sh$</td>
<td>s⁻¹</td>
<td>Jet shear rate, $U_0/h$</td>
</tr>
<tr>
<td>$St$</td>
<td>-</td>
<td>Stokes number</td>
</tr>
<tr>
<td>$T_{\text{HI}}$</td>
<td>-</td>
<td>Normalised eddy timescale, turbulent inertial regime</td>
</tr>
<tr>
<td>$T_{TV}$</td>
<td>-</td>
<td>Normalised eddy timescale, turbulent viscous regime</td>
</tr>
<tr>
<td>$U_0$</td>
<td>ms⁻¹</td>
<td>Average gap velocity</td>
</tr>
<tr>
<td>$u$</td>
<td>ms⁻¹</td>
<td>Local liquid velocity</td>
</tr>
<tr>
<td>$V_{\text{diss}}$</td>
<td>m³</td>
<td>Energy dissipation volume</td>
</tr>
<tr>
<td>$We_d$</td>
<td>-</td>
<td>Dynamic Weber number</td>
</tr>
<tr>
<td>$We_{\text{TI}}$</td>
<td>-</td>
<td>Inertial eddy Weber number</td>
</tr>
<tr>
<td>$x$</td>
<td>m</td>
<td>Distance in the x-direction from the gap entrance</td>
</tr>
</tbody>
</table>
Greek symbols

δ₁ m Displacement thickness
ε m²s⁻¹ Energy dissipation rate per unit mass
γ Nm⁻¹ Surface tension
η m Kolmogorov length scale
η_c Nm⁻² Dynamic viscosity of the continuous phase
η_d Nm⁻² Dynamic viscosity of the dispersed phase
ν m²s⁻¹ Fluid kinematic viscosity
ρ_c Kgm⁻³ Fluid density of the continuous phase
ρ_d Kgm⁻³ Fluid density of the dispersed phase
σ Pa Stress acting on the drop
τ_{def} s Drop deformation timescale
τ_{eddy} s Eddy timescale
τ_{particle} s The drop response time in laminar flow
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Finally my father, for making me an engineer in the first place.

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