Ballistic droplet interception (BALI)

van Gils, T.

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Master Thesis

Ballistic Droplet Interception (BALI)

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Summary

Nowadays, one of the major research topics in the printing world is related to inkjet printing in combination with so-called ‘rapid manufacturing’. Part of this research aims at printing of 3D structures, directly from CAD data. The focus is on the application of innovative materials, generally with a relatively high viscosity. For one of these projects, TNO Science and Industry realized a printing set-up which can process different materials. This system generates a continuous stream of small droplets ($R \approx 50 \mu m$), at high frequency ($f \approx 20 \text{ kHz}$). To be able to generate patterns from this continuous stream of droplets, individual droplets have to be steered to either reach the substrate or to be caught in a gutter followed by recycling. Currently this is done through selectively charging droplets, followed by deflection in an electrostatic field. The major drawback of this method is that it can only be applied to materials with sufficient electrical conductivity.

At this moment, no technology exists for the printing of highly viscous materials that are non-conductive. TNO is searching for new methods that allow printing of such materials. One of the options is selective droplet deflection using a microscopic air-jet. TNO has proven the working principle of this method in an experimental set-up, where droplets could be selectively deflected with a bandwidth up to 2 kHz. However, for industrial applications this bandwidth is far too low, so further fundamental knowledge is needed or another deflection method should be investigated. In this project a new deflection method is investigated, where a secondary print head with a “on demand” printable material is used to ballistically deflect the droplets. By carefully choosing the impact parameter and Weber number, a deflection without coalescence should be possible, so the recycling of the deflected droplets will be possible.

Using a continuous tri-ethylene glycol droplet stream, that has a viscosity of 38.8 mPa s, and a drop-on-demand print head which prints water droplets, a tri-ethylene glycol droplet collides with a water droplet and is deflected from the droplet stream. Looking at the results of the collision experiments, three regimes are found: bouncing, stretching separation and coalescence. Bouncing and stretching separation are preferred to be able to recycle the printed material that has been deflected. The impact parameter, $I = b(R_d + R_g)^{-1}$, of the collision determines which regime is the result of the collision. The range of impact parameters which satisfy the deflection conditions is $0.64 \leq I \leq 0.80$ for a Weber number, $We = \rho_d d_d^2 v_d^2 / \sigma_d$, of 160, and increases to $0.58 \leq I \leq 0.83$ for Weber numbers larger than 300.

Comparing the experiments with the theoretical predictions, it was found that there is a loss of kinetic energy during the collision. The major part of the kinetic energy loss can be explained by conversion into vibration and rotation energies. Also the presence of a boundary layer on the continuous droplet stream has influence on the droplet velocities. The thickness of this boundary layer around a 3D droplet stream can be described by the equation used for the boundary layer on a 2D continuous flat surface. This is valid for the situation of four droplets in a droplet stream, moved a small distance from the nozzle plate.

The use of collisions between droplets is an applicable method for deflection in an industrial printing process, but when the inkjet is printing for a longer period of time, the droplets in the stream show a deviation in their position: during 15 minutes, the vertical deviation in position is approximately one droplet diameter. This deviation gives problems controlling the impact parameter. The stability can be improved using a
feedback control loop which adjusts the amplitude of the signal to the piezo element in the print head. If one drops the recycling requirement, the method looks promising for industrial applications, because this method has shown the deflection of one single droplet from a continuous droplet stream.

In order to reach industrial applicability, the frequency of the generation of the DOD droplets should be increased. This can be done using multiple DOD print heads, or driving one print head at higher frequency. Note that the specifications of different DOD print heads show that higher frequencies are possible, but my experiments show that the stability of the DOD droplet stream is not good, so further investigation is needed.

Finally, the influence of deflecting more droplets from the continuous droplet stream is not investigated, yet. This can lead to an unstable droplet stream; however, when the distance between the deflection point and substrate is small, this instability is not expected to degrade droplet placement accuracy.
List of symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Unit</th>
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<tbody>
<tr>
<td>a</td>
<td>acceleration</td>
<td>[m²/s]</td>
</tr>
<tr>
<td>$A_{\text{frontal}}$</td>
<td>exposed frontal area droplet ($\pi R^2$)</td>
<td>[m²]</td>
</tr>
<tr>
<td>b</td>
<td>impact parameter</td>
<td>[m]</td>
</tr>
<tr>
<td>d</td>
<td>droplet diameter</td>
<td>[m]</td>
</tr>
<tr>
<td>g</td>
<td>acceleration due to gravity</td>
<td>[m²/s]</td>
</tr>
<tr>
<td>h</td>
<td>interaction region</td>
<td>[m]</td>
</tr>
<tr>
<td>L</td>
<td>distance between droplets in droplet stream</td>
<td>[m]</td>
</tr>
<tr>
<td>m</td>
<td>mass droplet</td>
<td>[kg]</td>
</tr>
<tr>
<td>P</td>
<td>distance between droplets centers</td>
<td>[m]</td>
</tr>
<tr>
<td>p</td>
<td>pressure</td>
<td>[Pa]</td>
</tr>
<tr>
<td>R</td>
<td>droplet radius</td>
<td>[m]</td>
</tr>
<tr>
<td>t</td>
<td>time</td>
<td>[s]</td>
</tr>
<tr>
<td>$U_0$</td>
<td>velocity of flat surface, cylinder or droplet stream in simulation</td>
<td>[m/s]</td>
</tr>
<tr>
<td>u</td>
<td>relative velocity of droplet</td>
<td>[m/s]</td>
</tr>
<tr>
<td>V</td>
<td>droplet volume before collision</td>
<td>[m³]</td>
</tr>
<tr>
<td>$V_i$</td>
<td>interacting volume of droplet in stretching separation</td>
<td>[m³]</td>
</tr>
<tr>
<td>v</td>
<td>velocity of the droplet</td>
<td>[m/s]</td>
</tr>
<tr>
<td>x</td>
<td>position of the droplet</td>
<td>[m]</td>
</tr>
<tr>
<td>$C_d$</td>
<td>drag coefficient</td>
<td>[-]</td>
</tr>
<tr>
<td>I</td>
<td>nondimensional impact parameter ($b(R_A + R_B)^{-1}$)</td>
<td>[-]</td>
</tr>
<tr>
<td>Re</td>
<td>Reynolds number ($\frac{\mu}{\rho} \frac{d}{v}$)</td>
<td>[-]</td>
</tr>
<tr>
<td>We</td>
<td>Weber number ($\frac{\rho d v^2}{\sigma}$)</td>
<td>[-]</td>
</tr>
</tbody>
</table>

Nondimensional numbers

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>angle of impact relative to relative velocity vector droplet A</td>
<td>[°]</td>
</tr>
<tr>
<td>$\beta$</td>
<td>angle of relative velocity vector with positive x-axis</td>
<td>[°]</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>angle of impact relative to position x-axis</td>
<td>[°]</td>
</tr>
<tr>
<td>$\delta_{\text{critical}}$</td>
<td>angle of deflection between trajectory and next droplet in stream</td>
<td>[°]</td>
</tr>
<tr>
<td>$\delta_{\text{ds}}$</td>
<td>boundary layer thickness of flow past a continuous flat surface</td>
<td>[m]</td>
</tr>
<tr>
<td>$\delta_{90,\text{cyl}}$</td>
<td>boundary layer thickness of flow past a cylinder</td>
<td>[m]</td>
</tr>
<tr>
<td>$\delta_{90,\text{ds}}$</td>
<td>boundary layer thickness of flow past a droplet stream</td>
<td>[m]</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>energy loss fraction</td>
<td>[-]</td>
</tr>
<tr>
<td>$\zeta$</td>
<td>angle of deflection droplet B in elastic collision</td>
<td>[°]</td>
</tr>
<tr>
<td>$\vartheta$</td>
<td>angle between relative velocity and y-axis</td>
<td>[°]</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>ratio of viscosities</td>
<td>[-]</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>elasticity number</td>
<td>[-]</td>
</tr>
<tr>
<td>$\mu$</td>
<td>dynamic viscosity</td>
<td>[Pa s]</td>
</tr>
<tr>
<td>$\rho$</td>
<td>density</td>
<td>[kg/m³]</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>surface tension</td>
<td>[N/m]</td>
</tr>
<tr>
<td>$\phi$</td>
<td>angle of deflection droplet A after collision</td>
<td>[°]</td>
</tr>
<tr>
<td>$\phi$</td>
<td>angle print heads relative to each other</td>
<td>[°]</td>
</tr>
<tr>
<td>$\chi$</td>
<td>angle of deflection droplet A in elastic collision</td>
<td>[°]</td>
</tr>
<tr>
<td>$\psi$</td>
<td>angle of deflection inelastic collision</td>
<td>[°]</td>
</tr>
</tbody>
</table>
Vectors
\( \mathbf{b} \) impact parameter vector [m]
\( \mathbf{e} \) unity vector [-]
\( \mathbf{g} \) gravitational acceleration \([\text{m}^2/\text{s}^2]\]
\( \mathbf{L} \) angular momentum \([\text{kg m}^2/\text{s}]\]
\( \mathbf{r} \) distance vector for radii droplets [m]
\( \mathbf{u} \) relative velocity droplets [m/s]
\( \mathbf{v} \) velocity droplets [m/s]
\( \mathbf{x} \) position of droplets [m]

Forces
\( \mathbf{F}_d \) total drag force acting on droplets [N]
\( \mathbf{F}_{\text{drag}} \) longitudinal component of drag force acting on droplets [N]
\( \mathbf{F}_g \) gravitational force [N]
\( \mathbf{F}_{\text{Saff}} \) Saffman lift force [N]
\( \mathbf{F}_{\text{react}} \) transversal reacting force of drag force acting on droplets [N]

Energies
\( E_{\text{heat}} \) heating energy during collision [J]
\( E_{\text{kin},1} \) kinetic energy before the collision [J]
\( E_{\text{kin},2} \) kinetic energy after the collision [J]
\( E_{\text{str}} \) stretching energy [J]
\( E_{\text{surf}} \) surface tension energy [J]
\( E_{\text{rot}} \) rotation energy [J]
\( E_{\text{vibr}} \) vibration energy [J]

Subscripts
1 before the collision
2 after the collision
A droplet A
air air
B droplet B
cylyn cylinder
d droplet/fs continuous flat surface
rel relative
t tangential component
TEG tri-ethylene glycol
x in x-direction
y in y-direction
\( \gamma \) in \( \gamma \)-direction
\( \perp \) perpendicular (normal) component
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B Drag force relations and constants  
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F Trajectory droplet after collision
1 Introduction

Inkjet printing is a common and wide spread technology. This form of printing is used to make two-dimensional patterns, where a substrate is moving and a structure of single droplets is made, but is also used in manufacturing (3D) processes. Deposition of small droplets, layer on layer on a moving substrate, grows a three-dimensional structure [1]. In normal inkjet printing, there is a restriction of viscosity (liquids with a viscosity up to 30 mPa s can be printed). The advantage of the used print head in this project is that it can print liquids with a viscosity between 2 and 500 mPa s. Because the droplets used in this printing process are small (35 to 250 µm), precise structures can be created, and also small series of functional parts can be created fast. The advantage of the small droplets for the 2D printing is that polymers with long molecule chains can be printed. The inkjet technology can be distinguished into two primary methods, the continuous printing and drop-on-demand printing. In the continuous method, a continuous droplet stream is generated. This droplet stream is liquid that flows through a nozzle, forms a jet and breaks up into separate droplets [2], and is controlled using a piezo element, which accelerates the liquid using a pressure pulse. This piezo element controls the frequency of the droplets and the distance between the droplets. In the drop-on-demand method the droplet is generated using a pressure pulse which ejects a droplet from a reservoir through a nozzle. This pressure pulse can be generated piezo-electrically or thermally. The drop-on-demand method is not a continuous process, but a droplet can be generated, as its name already explains, on demand. The drop-on-demand print head cannot print highly viscous liquids. This is also shown in Table 1.1.

<table>
<thead>
<tr>
<th></th>
<th>CIJ</th>
<th>DOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Printing frequency</td>
<td>10 - 140 kHz</td>
<td>1 Hz - 20 kHz</td>
</tr>
<tr>
<td>Viscosity</td>
<td>2 - 500 mPa s</td>
<td>up to 40 mPa s</td>
</tr>
<tr>
<td>Droplet diameter</td>
<td>30 - 250 µm</td>
<td>40 - 75 µm</td>
</tr>
<tr>
<td>Droplet velocity</td>
<td>8 - 11 m/s</td>
<td>0.75 - 2 m/s</td>
</tr>
</tbody>
</table>

For the creation of a 3D structure or 2D print, not all droplets from the droplet stream should reach the substrate; in other words, most droplets should be deflected from the droplet stream, such that droplets will not reach the substrate.

If the used liquid is electrically charged, using electrodes to deflect the droplets from the stream is a possibility. If the droplet should be deflected, the charging electrode charges only the droplet that should be deflected. This is schematically shown in Figure 1.1. The deflection electrode is a static electrode, which means there constantly a voltage on the electrodes. The charged droplets are deflected by this electrode, the uncharged droplets are undisturbed and reach the substrate. The deflected droplets can be collected and recycled if necessary.

To create structures, like ceramic components [3] or organic implants [4] (an example of an implant jaw is given in Figure 1.2), more viscous (or highly viscous), non-conductive materials are needed. This is also the case for printing long polymers, wherefore highly viscous materials are required. The droplets in these droplet streams should also be deflected, but now the electrodes don’t work. Making these materials conductive is not an option because this changes the properties of the materials. Therefore, other deflection methods are needed.
The deflection of droplets using an air flow is one alternative method. The advantage of this air flow is that the deflected droplets are not contaminated by the air, and after collecting the droplets, the droplets can be recycled. Because these highly viscous materials can be expensive, this recycling is desirable requirement. The air flow can be applied in several methods, where one method is placing a hollow needle on a piezo stack. This piezo stack is translating to the stream if the droplet should be deflected, and is translated back to its initial position, when the droplet should not be deflected. To collect the deflected droplets for recycling, the deflection should be at least 2°. At 2° deflection it is possible to collect the droplet just below the point of deflection (about 30 mm), taking into account instability of the droplet stream of 1 droplet diameter (i.e. the droplet stream can vary in horizontal position at certain distances under the nozzle plate) and the thickness of the collecting container. This also gives the advantage that the distance between the nozzle of the print head and the substrate is small (about 50 mm), which is an advantage for a stable printing process.

Experiments done by Oosterhuis et al. [5] showed that the droplet deflection of 2° is possible using this mechanically movable piezo stack at a frequency of 1.6 kHz. Because this frequency is low in comparison with the preferable printing frequency of 20 kHz (and in the future up to 140 kHz), a higher translation frequency for the needle is needed. This has fundamental problems, because it is hard to move mechanically with a frequency of 20 kHz (e.g. to deflect droplets with a diameter of 100 µm, an acceleration of the needle of 4·10^5 m/s^2 is necessary). Solutions for this problem can be the use of a constant air jet, where a foil is used to deflect the air jet if the droplet should not be deflected from the stream. This effect is known as the Coanda effect. Another possibility could be the use of a multi-nozzle system, where multiple needles are placed vertically under each other. The extra effect here is the air jet interaction between the different air jets from the nozzles. Both deflection methods are shown in Figure 1.3.

Using an air flow is not the only possibility to deflect the droplets, where the droplets in the droplet stream are not contaminated: ballistic interception, or in other words, high frequent billiards with droplets is another possibility. In this method, two droplets are ‘shot’ onto each other, so the two droplets collide and after the collision, both droplets are deflected from their original trajectory. The droplet from the continuous droplet
stream is deflected and can be collected. The results of the collisions can be separated into different regimes, where bouncing is the most preferable. This bouncing is comparable with a complete elastic collision, which means the two droplets do not merge or contaminate each other. Coalescence, which is comparable with a total inelastic collision, is not preferable, because here the two droplets become one droplet after the collision, so after the collision they cannot be recycled.

1.1 **Aim of the project**

First of all, the stability of the droplet stream is investigated. If the droplet stream is stable enough to control the impact parameter of the collision, the collisions are used to deflect the droplets from the continuous droplet stream. The impact parameter is varied to investigate the different regimes which are the result of the collision. Also the range of impact parameters is investigated for different Weber numbers \( \text{We} = \frac{\rho_f d_v v^2}{\sigma_f} \). These results are compared with the theoretical curves found by others, for the bouncing, stretching separation and coalescence. The velocities of the droplets after the collision are determined from the experiments and compared with the theoretical calculated velocities. And, finally, the range is determined for which impact parameters the deflection of the droplet from the continuous droplet stream is at least 2°.

Figure 1.2 Implant 3D printed jaw, an example of the application of 3D printing.

Figure 1.3 a) the Coanda effect and b) the multi-nozzle system. Both are possible methods to deflect a droplet from a continuous droplet stream using an air jet, but from both methods, the extra effects on the droplet stream are unknown.
1.2 Thesis outline

To understand the behaviour of the droplets and the parameters that are important for a successful collision, the theory of this is described in chapter 2. This chapter also describes the collision of the droplet itself and deals with the external forces acting on the droplets, like air drag and gravity. Also the influence of the presence of a boundary layer on the continuous droplet stream on the collision is investigated using numeric simulations. In chapter 3 the experimental set-up used for the droplet collisions, is described. Special attention is given to the used light source to illuminate the droplets, the materials for the droplets and the analysis of the pictures. Because the print heads are of importance in this set-up, both print heads are described here as well. The experimental results of the stability of the print heads, the droplet collisions itself and the regimes of the results are showed in chapter 4. Here also the experimental results are compared with the experiments done by others. Finally, in chapter 5 the conclusions are drawn and recommendations for future research and applications are given.
2 Theory

In this chapter the theory of the colliding droplets is discussed. First, dimensionless numbers are introduced. Because droplets can be considered as spheres in good approximation, the elastic and inelastic collisions of two solid spheres are described. The result of the colliding droplets depends on the impact parameter. The results can be classified into different regimes, so these different regimes are discussed. The theoretical feasibility of deflection of individual droplets out of a droplet stream by collisions with other droplets is investigated before the experimental collisions themselves.

The droplets are moving in air, so external forces like air drag and gravity, have influence on the droplets. The magnitude and direction of the drag force on a droplet leaving the continuous droplet stream is analyzed. Also, a boundary layer is created on the continuous droplet stream. This boundary layer is investigated using numerical simulations.

2.1 Fluid dynamics

In fluid dynamics flows of Newtonian fluids (fluids which viscosity is shear independent) are described by the reduced equation of conservation of mass, due to incompressibility

$$\nabla \cdot \vec{\nu} = 0,$$

and the equation of conservation of momentum

$$\rho \frac{\partial \vec{\nu}}{\partial t} + \rho (\vec{\nu} \cdot \nabla) \vec{\nu} = -\nabla p + \mu \nabla^2 \vec{\nu} + \rho \vec{g},$$

where $\nabla$ is the nabla-operator and $\vec{\nu}$ the velocity vector, $\rho$ is the fluid density, $p$ the pressure, $\mu$ the dynamic viscosity and $\vec{g}$ the gravitational acceleration [6]. Equation 2.2 is also called the Navier-Stokes equation. In general this Navier-Stokes equation is non-linear and analytical solutions are hard to find. Therefore, approximations where one or more terms are neglected are investigated and solved. In the next paragraph, two dimensionless numbers are introduced, which are useful in this project.

2.2 Dimensionless numbers

Dimensionless numbers are products or ratios of physical quantities where all units cancel. For collisions of droplets, two numbers are important, which are the Reynolds number and the Weber number.

2.2.1 Reynolds number

The Reynolds number is the ratio between the inertial forces and the viscous forces, acting on the fluid. The Reynolds number for a moving (liquid) droplet in (stationary) air is defined as

$$\text{Re} = \frac{\rho \vec{\nu} \delta}{\mu},$$

where $\rho$ and $\mu$ are the fluid density and the dynamic viscosity, $\vec{\nu}$ is the velocity vector of the fluid, and $\delta$ is the characteristic length of the droplet. In the case of a droplet stream, $\delta$ is the diameter of the droplets.

---

Footnote: $\nabla \equiv \frac{\partial}{\partial x} \hat{i} + \frac{\partial}{\partial y} \hat{j} + \frac{\partial}{\partial z} \hat{k}$, where $\hat{i}$, $\hat{j}$ and $\hat{k}$ are the unit vectors in the $x$-, $y$- and $z$-direction of the Cartesian coordinate system.
\[
\text{Re} = \frac{\rho_{\text{air}} v_d d_d}{\mu_{\text{air}}},
\]

(2.3)

where \(\rho_{\text{air}}\) is the density of air, \(v_d\) is the velocity of the droplet, \(d_d\) the typical diameter of the droplet and \(\mu_{\text{air}}\) the dynamic viscosity of air.

### 2.2.2 Weber number

The Weber number is the ratio of the kinetic energy and the surface energy of the droplet (or ratio of inertia and the surface tension of the droplet), and is given by

\[
\text{We} = \frac{\rho_d d_d v_d^2}{\sigma_d},
\]

(2.4)

in which \(\sigma_d\) is the surface tension of the droplet.

In the experiments with droplets done by others, like Qian and Law and Estrade et al. ([7]–[10]), the droplets used for the collision are equal-sized and of the same liquid, and therefore the Weber number is defined as in Equation 2.4. The results of the collisions are given as function of the Weber number. In this project, two unlike-liquid droplets with non-equal sizes are used. This means that the ‘collision system’ has two Weber numbers before the collision. Therefore, the ratios of density, viscosity and surface tension are important as well to describe the collision using one Weber number. But, as will be learned later, coalescence or stretching separation as result of the collision is determined by the strength of the liquid ‘bridge’ formed after the collision. This bridge is as strong as the surface tension of the weakest liquid. Therefore, for the collisions one Weber number is defined, using the properties of the droplet with the lowest surface tension [11] and the relative velocity (see 2.3.1).

### 2.3 Elastic and inelastic collisions

The droplets used for printing have a lot of similarities with rigid spheres. Therefore, to describe the collisions of two droplets, first the collisions of rigid spheres will be described. Because the droplets are moving with respect to each other, first the used frames of reference are described. Then, paragraph 2.3.2 describes the inelastic collision, paragraph 2.3.3 deals with the elastic collision. This section ends with the introduction of the impact parameter.

#### 2.3.1 Frames of reference

To describe the collision of two moving droplets, it is sometimes easier to use a frame of reference. The origin of which is situated in the center of droplet A, and moves with the velocity of droplet A before the collision (i.e. the initial velocity of droplet A), which gives the relative velocity from one droplet with respect with to the other droplet. The frame of reference is drawn in Figure 2.1. In a) the ‘real’ velocities of the droplets are shown, i.e. the velocities relative to the lab-frame of reference; in the rest of this thesis the real velocities before the collision are given by \(\mathbf{\tilde{v}}_{A1}\) and \(\mathbf{\tilde{v}}_{B1}\). After the collision these velocities are given by \(\mathbf{\tilde{v}}_{A2}\) and \(\mathbf{\tilde{v}}_{B2}\). In b) the relative velocities of the droplets are given, where the relative velocity of droplet A is \(\mathbf{\tilde{u}}_{A1} = 0\) and \(\mathbf{\tilde{u}}_{B1} = \mathbf{\tilde{v}}_{B1} - \mathbf{\tilde{v}}_{A1}\).
2.3.2 Completely inelastic collisions

In the classic situation, two rigid spheres, initially moving in perpendicular direction, making an inelastic collision are shown in Figure 2.2. Only the conservation laws, which determine the velocities after the collision, are shown but are not solved. This will be done in section 2.5. From the conservation law for momentum, the velocity and the angle after the collision could be determined:

\[
\begin{align*}
\text{x-coordinate:} & \quad m_B v_{B1} = (m_A + m_B) v_C \cos \psi \\
\text{y-coordinate:} & \quad m_A v_{A1} = (m_A + m_B) v_C \sin \psi
\end{align*}
\]  

(2.5)

where \( m_A \) and \( m_B \) are the mass of sphere A and B resp. and \( v_C \) the velocity of the coagulated spheres.

Figure 2.1 Frames of reference for the colliding droplets, a) the ‘real’ velocities of the droplets, b) the ‘relative’ velocities of the droplets in the new frame of reference, where the origin of the frame of reference is moving with velocity \( \mathbf{v}_{A1} \).

Figure 2.2 Inelastic collision of two rigid spheres: situation a) before the collision, situation b) after the collision.

2.3.3 Elastic collisions

A schematic overview of the elastic collision of two droplets is given in Figure 2.3. For determination of the angles of deflection, the conservation laws for momentum and kinetic energy are used, which gives

\[
\begin{align*}
\text{momentum x-direction:} & \quad m_B v_{B1} = m_A v_{A2} \cos \zeta + m_B v_{B2} \cos \zeta, \\
\text{momentum y-direction:} & \quad m_A v_{A1} = m_A v_{A2} \sin \zeta + m_B v_{B2} \sin \zeta, \\
\text{kinetic energy:} & \quad \frac{1}{2} m_A v_{A1}^2 + \frac{1}{2} m_B v_{B1}^2 = \frac{1}{2} m_A v_{A2}^2 + \frac{1}{2} m_B v_{B2}^2,
\end{align*}
\]  

(2.6) (2.7) (2.8)

where \( \zeta \) and \( \chi \) the angles of reflection after the collision.
Now also another relation is needed to determine the velocities and angles after the collision: the conservation of angular momentum. The angular momentum is defined as

\[ \overline{L} = \mathbf{r} \times \mathbf{p} = \mathbf{r} \times m \mathbf{v}, \]

and is given in Figure 2.4, which gives for the velocity components

\[ (R_A + R_B) \cdot u_{B1,\perp} = |\overline{L}_1| = |\overline{L}_2| = (R_A + R_B) \cdot u_{B2,\perp} \Rightarrow u_{B1,\perp} = u_{B2,\perp}. \]

See appendix A for the transformation into these coordinates.

2.3.4 Impact parameter

The angle of deflection can be written in terms of another important parameter during the collision, the impact parameter, \( b \). This impact parameter is defined as the distance from the centre of one droplet to the relative velocity vector placed on the centre of the other droplet [10], so the nondimensional impact parameter is given by

\[ I = \frac{b}{R_A + R_B}, \]

and is shown in Figure 2.5. This means that a head-on collision (the relative velocity vector coincides with the center-to-center line) is described as \( I = 0 \) and for \( I = 1 \) the droplets just collide at the boundaries.
The angle of impact relative to the relative velocity vector for droplet A is

\[ \sin \alpha = \frac{b}{R_A + R_B} = I. \quad (2.12) \]

2.3.5 Elasticity number \( \lambda \)

The droplets are not solid spheres, but sphere-shape liquids, so there is a complete regime between a completely elastic collision and a complete inelastic collision. Therefore, a number of elasticity, \( \lambda \), is introduced. This number determines the elasticity of the collision. The most common situations for the collisions are coalescence of the two droplets (will be explained in paragraph 2.4.1), where \( \lambda = 1 \). For a completely elastic collision, \( \lambda = 0 \). During the collision, also mass transfer is possible, so droplet A or droplet B increases in volume. This results in the elasticity number \( 0 < \lambda < 1 \).

Using this elasticity number, relations for the velocities of the droplets after the collision can be derived, using Equation 2.10 and the following equations ( \( \ddot{u}_{A1} = 0 \) )

\[ m_B \ddot{u}_{B1} = m_C \ddot{u}_{A2} + m_D \ddot{u}_{B2}, \quad (2.13) \]

\[ \frac{1}{2} m_B \ddot{u}_{B1}^2 = \frac{1}{2} m_C \ddot{u}_{A2}^2 + \frac{1}{2} m_D \ddot{u}_{B2}^2. \quad (2.14) \]

\[ m_C = \lambda m_B + m_A \quad \Rightarrow \quad -\frac{m_A}{m_B} \leq \lambda \leq 1. \quad (2.15) \]

\[ m_D = (1 - \lambda)m_B \]

At the position of impact, the relative velocity vector can be separated into two components: a tangential and a normal component (see also appendix A),
\[ \vec{u}_{B1} = u_{B1,x} \cdot \vec{e}_x + u_{B1,y} \cdot \vec{e}_y = u_{B1,\perp} \cdot \vec{e}_\gamma + u_{B1,\parallel} \cdot \vec{e}_\frac{\pi}{2}, \]  
(2.16)

where the normal and tangential component are given by, respectively
\[ u_{B1,\perp} = u_{B1,x} \cos \gamma + u_{B1,y} \sin \gamma, \]
\[ u_{B1,\parallel} = -u_{B1,x} \sin \gamma + u_{B1,y} \cos \gamma. \]  
(2.17)

Now using these relations and the relation found in Equation 2.10, the relative velocities after the collision are given by [12]
\[ \vec{u}_{A2} = \left( \frac{2 - \lambda}{m_A + m_B} \right) u_{B1,\perp} \cdot \vec{e}_\gamma \]
\[ \vec{u}_{B2} = \left( \frac{1 - \lambda}{m_A + m_B} \right) u_{B1,\perp} \cdot \vec{e}_\gamma + u_{B1,\parallel} \cdot \vec{e}_\frac{\pi}{2}. \]  
(2.18)

2.3.6 Determination of impact parameter from two pictures before collision

Determination of the impact parameter for the collisions is possible using two pictures, at two different times before the collision. Using the two pictures and the time between them, the velocities of the droplets can be calculated. This gives
\[ \vec{v}_{A1} = \begin{pmatrix} v_{A1,x} \\ v_{A1,y} \\ v_{A1,z} \end{pmatrix} \quad \text{and} \quad \vec{v}_{B1} = \begin{pmatrix} v_{B1,x} \\ v_{B1,y} \\ v_{B1,z} \end{pmatrix}. \]  
(2.19)

The positions of the droplets before the collision, as shown in Figure 2.6, are
\[ \vec{x}_A (t) = \begin{pmatrix} x_A (t) \\ y_A (t) \\ z_A (t) \end{pmatrix} \quad \text{and} \quad \vec{x}_B (t) = \begin{pmatrix} x_B (t) \\ y_B (t) \\ z_B (t) \end{pmatrix}. \]  
(2.20)

Using these equations, the trajectories of both droplets until the collision can be calculated, using
\[ \vec{x}_A (t) = \vec{x}_A (t_0) + (t - t_0) \vec{v}_{A1}, \quad t - t_0 << 1 \text{ ms.} \]  
(2.21)

For determination of the impact parameter, droplet A is placed in the origin of a new coordinate system, which transforms Equation 2.21 into
\[ \vec{x}_A' (t) = 0 \]
\[ \vec{x}_B' (t) = \vec{x} + (t - t_0) \vec{v}, \]  
(2.22)

where \( \vec{x} \equiv \vec{x}_B - \vec{x}_A \) and \( \vec{v} \equiv \vec{v}_B - \vec{v}_A. \)
The impact parameter is the distance of the line $\mathbf{x}_B(t)$ to the origin of droplet $A$,
\[
\mathbf{b} = \mathbf{x}(t_b) = \mathbf{x}(t_0) + (t_b - t_0)\mathbf{v}.
\] (2.23)

The impact parameter vector is perpendicular to the velocity vector, so
\[
\mathbf{b} \cdot \mathbf{v} = 0,
\] (2.24a)
\[
(\mathbf{x}(t_0) + (t_b - t_0)\mathbf{v}) \cdot \mathbf{v} = 0,
\] (2.22b)
\[
\mathbf{x}(t_0) \cdot \mathbf{v} + (t_b - t_0)(\mathbf{v} \cdot \mathbf{v}) = 0,
\] (2.22c)
\[
t_b - t_0 = -\frac{\mathbf{x}(t_0) \cdot \mathbf{v}}{\mathbf{v} \cdot \mathbf{v}}.
\] (2.22d)

The impact parameter vector is now given as
\[
\mathbf{b} = \mathbf{x} - \mathbf{x} \cdot \frac{\mathbf{v}}{|\mathbf{v}|} \mathbf{v} = \mathbf{x} - \frac{(\mathbf{x} \cdot \mathbf{v}) \mathbf{v}}{|\mathbf{v}|^2},
\] (2.25)

where $b = |\mathbf{b}|$. Equation 2.25 is therefore valid both for the 2D and 3D geometry.

2.4 Collision results

The results of the collisions between two droplets can be classified into different regimes. This outcome is dependent on the impact parameter of the collision, but also on the velocity of the droplets. The most common regimes, bouncing, coalescence, reflective separation and stretching separation, which are shown in Figure 2.8, are explained in more detail in the next sections.

2.4.1 Coalescence

In a collision of two droplets, the droplets merge at the moment that the two surfaces of the droplets touch each other. The mass of one droplet flows into the other droplet and this combined mass will oscillate until a spherical drop is formed. This type of collision is best comparable with a completely inelastic collision.
2.4.2 Reflective separation
Two droplets collide and coalesce temporarily. The liquid in the two colliding droplets will spread radially in the plane of their center-to-center line. This will form a torus-like droplet (example pictures given in e.g. Ashgriz and Poo [10]). Due to the large curvature at the boundary of the droplet, there is a pressure difference between the inner and outer region of this droplet. Liquid is pushed out of its center and a (asymmetric) column is formed. This column will break into two (or more) droplets after the reflective action of the surface tension forces. This is shown in Figure 2.7.

![Figure 2.7 Reflective separation.](image)

2.4.3 Stretching separation
Stretching separation occurs, normally, at higher impact parameters. During the collision, only a small part of the droplets will be in direct contact with each other. These regions try to hold the droplets together, due to the surface energy in this region. The parts of the droplets which are not in contact, try to flow in the direction of the initial trajectory.
Since the two droplets are not equal in size, the smaller droplet (the surface tension of which is also higher than the surface tension of the bigger droplet) has a higher pressure than the bigger droplet and during the collision a pressure difference occurs. Liquid of the smaller droplet will try to flow into the bigger droplet. Separation occurs when the stretching energy is bigger than the surface energy. This stretching energy is the part of the drop kinetic energy which is trying to stretch and separate the interacting areas. During this separation, satellite droplets can be generated.

2.4.4 Bouncing
When two droplets in air come close together, the gas layer may get trapped between them. The pressure in this layer will increase. If the relative velocity of the droplets is not enough to overcome the pressure force, the two droplets do not contact each other and bounce away from each other, where deformation occurs or not. This bouncing principle is best comparable with an elastic collision.
2.5 Deflection of droplets

Different results of the collisions are possible, as explained in the upper sections, but for the industrial application of this deflection method, the angle of deflection should be at least 2° and the droplets should be recycled after the collisions. The most preferable collision results are bouncing or stretching separation (without mass transfer). Required is also that the deflected droplet will not coalesce with the next droplet in the droplet stream, after the collision.

Assume a collision of a droplet with diameter $d_A$, velocity $\vec{v}_A$, mass $m_A$ with a droplet with diameter $d_B$, velocity $\vec{v}_B$, mass $m_B$, initially placed under an angle $\phi$ with respect to $\vec{v}_A$. The situation is shown in Figure 2.9 a). This gives
\[ \mathbf{v}_{A1} = \begin{pmatrix} v_{A1,x} \\ v_{A1,y} \end{pmatrix} \text{ and } \mathbf{v}_{B1} = \begin{pmatrix} \sin \phi \\ \cos \phi \end{pmatrix} |\mathbf{v}_{B1}| = \begin{pmatrix} v_{B1,x} \\ v_{B1,y} \end{pmatrix}. \]  
(2.26)

The relative velocity of droplet B is

\[ \mathbf{u}_{B1} = \mathbf{v}_{B1} - \mathbf{v}_{A1}. \]  
(2.27)

The angle of the relative velocity vector with the positive x-axis, \( \beta \), is

\[ \beta = \frac{\pi}{2} + \theta, \text{ where } \tan \theta = \frac{u_{B1,x}}{u_{B1,y}}. \]  
(2.28)

The nondimensional impact parameter is still undetermined. With this impact parameter, the angle of impact relative to \( \mathbf{u}_{B1} \), \( \alpha \), is determined, using Equation 2.12. The angle of impact relative to the positive x-axis, \( \gamma \), is now given by

\[ \gamma = \alpha + \beta. \]  
(2.29)

The relative velocities after the collision are determined in Equation 2.18, so the ‘real’ velocities after the collision are now given by

![Diagram showing droplets before and after collision](image.png)

Figure 2.9  
a) Collision of a small droplet and a bigger droplet in a stream, b) deflection angle of droplet A after the collision.
Using these equations, it is now possible calculating the deflection angle of droplet A, \( \phi \), as shown in Figure 2.9 b)

\[
\tan \phi = \frac{V_{A2,x}}{V_{A2,y}}. \tag{2.31}
\]

In Figure 2.10 the deflection angle of droplet A is given as function of different impact parameters. Asymmetry, which can be seen in all graphs, is explained by the fact that droplet B has an x-component in its velocity before the collision in the negative x-direction, which deflects, after the collision, droplet A more to the left.

Another parameter is also important for the success of the collision: after the collision, the distance between the affected droplet and the next droplet in the stream should be larger than the diameter of this droplet, otherwise these two droplets will coalesce. This distance is dependent on the impact parameter (point of impact) and the distance between the droplets in the stream.

To investigate the impact parameter as function of the distance between the droplets (distance \( L \) in Figure 2.9 a ) and the velocity of the smaller droplet before the collision, angle \( \delta \) should be determined.
\[ \delta = \arcsin \left( \frac{P}{L + d_A} \right) \rightarrow \delta_{\text{critical}} = \arcsin \left( \frac{P_{\text{critical}}}{L + d_A} \right) = \arcsin \left( \frac{d_A}{L + d_A} \right). \quad (2.32) \]

Because \( \delta_{\text{critical}} = \alpha_{\text{critical}} + \theta \),

\[ \alpha_{\text{critical}} = \arcsin \left( \frac{d_A}{L + d_A} \right) - \arctan \left( \frac{u_{B1,x}}{u_{B1,y}} \right) = \arcsin \left( \frac{d_A}{L + d_A} \right) - \arctan \left( \frac{v_{B1,x}}{v_{B1,y} - v_{A1,y}} \right). \quad (2.33) \]

This gives for the critical impact parameter, using Equation 2.33,

\[ I_{\text{critical}} \left( \vec{v}_{B1}, L \right) = \sin \left( \alpha_{\text{critical}} \right), \quad (2.34) \]

or in a graph, as shown in Figure 2.11. From this figure the conclusion can be taken that the critical impact parameter \( I_{\text{critical}} > 0.5 \) for a successful bouncing or stretching separation collision, but as the velocity increases (the general velocity is 1.5 m/s), the critical impact parameter decreases. For the experiments the velocity of the DOD droplet is 1.5 m/s and the distance between the CIJ droplets is (approximately) three droplet diameters, which gives \( I_{\text{critical}} > 0.13 \).

![Graph showing impact parameter as function of droplet velocity and distance between the droplets in the stream. Diameter of the droplets is \( d_A = 110 \) µm and \( d_B = 55 \) µm, \( v_{A1,y} = 8 \) m/s.](https://example.com/graph.png)

Using this impact parameter, the distance between the affected droplet and the next droplet in the stream as function of the impact parameter is given as

\[ P(I) = (L + d_A) \sin(\delta_{\text{critical}}(I)). \quad (2.35) \]

The distance \( P(I) \) and the deflection angle as function of the impact parameter are shown in Figure 2.12. From the figure the conclusion can be taken that the impact parameter \( 0.5 \leq I \leq 0.97 \) to get a deflection of 2° after the collision and the affected droplet will not mix, coalesce or collide with the next droplet in the stream, assuming \( \lambda = 0 \).
2.6 Air drag and gravity influence

The droplets move in air so air drag and gravity have influence on the trajectory of the droplet. Therefore the influence of the gravity and air drag will be investigated.

2.6.1 Gravity influence

First, the influence of the gravity is investigated. When the air resistance is neglected, only the gravity has constant influence on the movement of the droplet. The trajectory of the droplet is given in Figure 2.13.

First, the case where $\phi_{initial} = 0^\circ$:

At time $t = 0$, the initial velocity is $\vec{v}_{initial} = (v_{x0}, v_{y0}) = (v_0, 0)$.

For $t > 0$, the velocity of the droplet is given by

$$v_x = v_{x0}$$

$$v_y = v_{y0} - \frac{1}{2} gt^2$$

(2.36)

so the position of the droplet is now given by

$$x = x_0 + v_x t = v_0 t$$

$$y = y_0 + v_y t = -\frac{1}{2} gt^2$$

(2.37)

where $x_0$ and $y_0$ are zero. The angle in trajectory for the droplet will be
\[ \phi = \arctan \left( \frac{v_y}{v_x} \right) = \arctan \left( \frac{-gt}{2v_x} \right) = \arctan \left( \frac{-gx}{2v_x^2} \right). \] (2.38)

If the initial angle \( \phi_{\text{initial}} \neq 0^\circ \), the initial velocity is
\[ \vec{v}_{\text{initial}} = (v_{x0}, v_{y0}) = (v_0 \cos \phi, v_0 \sin \phi). \] At \( t > 0 \), the velocity of the droplet is given by Equation 2.36, so the position of the droplet becomes
\[ x = v_0 \cos \phi \cdot t \]
\[ y = v_0 \sin \phi \cdot t - \frac{1}{2} gt^2. \] (2.39)

The absolute velocity is given as
\[ v_x = v_0 \cos \phi \]
\[ v_y = v_0 \sin \phi - gt \]
\[ \left| \vec{v} \right| = \sqrt{v_x^2 + v_y^2} = \sqrt{v_0^2 + gt(2v_0 \sin \phi)}. \] (2.40)

The angle in trajectory of the droplet remains the same as given in the first right hand side equation of Equation 2.38.

2.6.2 Air drag

When a droplet moves through vacuum, no external forces exerts onto the droplet and the droplet will move with a constant velocity (according to Newton’s Second Law, [14]). But when the droplet moves in air, the air exerts a friction (resistance) onto the droplet, which is called the air drag.

For rigid spheres moving through the air, the force acting on the sphere due to the air resistance is given by [15]:
\[ \vec{F}_d = \frac{1}{2} \rho_{\text{air}} A_{\text{frontal}} \, C_D(\text{Re}) \left| \vec{v} \right| \vec{v}, \] (2.41)

where \( \rho_{\text{air}} \) is the density of air, \( A_{\text{frontal}} \) the exposed frontal area of the droplet to the air and \( C_D(\text{Re}) \) the drag coefficient as function of the Reynolds number of the droplet, as given in Equation 2.3. For a rigid sphere, the influence of the gravity and air drag is given by Newton’s Second Law
\[ m \frac{d\vec{v}}{dt} = \sum \vec{F} = \vec{F}_g + \vec{F}_d = \begin{pmatrix} 0 \\ -mg \end{pmatrix} - \frac{1}{2} \rho_{\text{air}} A_{\text{frontal}} \, C_D(\text{Re}) \sqrt{v_x^2 + v_y^2} \begin{pmatrix} v_x \\ v_y \end{pmatrix}. \] (2.42)

The drag coefficient \( C_D \) as function of the Reynolds number is given by the relations as shown in Table B 1.

Fluid spheres could also have internal circulations, due to high ratio of the viscosities
\[ \kappa = \frac{\mu_d}{\mu_{\text{medium}}}, \] (2.43)

where \( \mu_d \) is the dynamic viscosity of the droplet and \( \mu_{\text{medium}} \) is the dynamic viscosity of the medium in which the droplet is moving. For a Stokes flow, where \( \text{Re} \ll 1 \), the drag coefficient found by Hadamard and Rybczynski (1911) is given by [16]
\[ C_D = \frac{8}{\text{Re}} \left( \frac{3\kappa + 2}{\kappa + 1} \right). \] (2.44)

The drag coefficient on a sphere, valid for \( 4 < \text{Re} < 100 \), is given by [16]
\[ C_D = \frac{3.05(783\kappa^2 + 2142\kappa + 1080)}{(60 + 29\kappa)(4 + 3\kappa)}\text{Re}^{-0.74}. \] (2.45)

The Reynolds number for a moving water droplet \( (v_d = 1.5 \text{ m/s}) \) with a diameter of 55 \( \mu \text{m} \) is 5.5, so the expression for the drag coefficient is valid. Also for a droplet \( (d_d = 110 \mu \text{m}, v_d = 8.5 \text{ m/s}) \) with \( \text{Re} = 62 \), this expression is valid. The drag coefficient depends also on the position of the droplet in the stream and on the stream configuration.

For comparison, the difference between the drag coefficient for a liquid water droplet \( (\kappa \approx 55) \) and a solid sphere \( (\kappa \rightarrow \infty) \), is \( C_D(\kappa \approx 55) = 0.988 \cdot C_D(\kappa \rightarrow \infty) \). This means that the internal circulation has only little effect on the drag.

Using Equations 2.42 and 2.45, and taking in mind that

\[ A_{\text{frontal}} = \frac{\pi}{4} d_d^2, \] (2.46a)

\[ m_d = \frac{\pi}{6} d_d^3 \rho_d, \] (2.46b)

\[ \text{Re}_d = \frac{\rho_{\text{air}} d_d v_d}{\mu_{\text{air}}} = \frac{\rho_{\text{air}} d_d \sqrt{v_x^2 + v_y^2}}{\mu_{\text{air}}}, \] (2.47)

the trajectory of water droplets travelling with different initial velocities and ejected under different angles \( \varphi \) with respect to the x-axis, can be calculated (procedure given in appendix B). The results are given in Figure 2.14.

In the experiments, the distance between the DOD print head and the CIJ droplet stream is small \(< 3 \text{ mm}\). From the figure it can be seen that water droplets, initially ejected under an angle with respect to the x-axis, experiences less effects of the air drag and gravity force, until this working distance. In other words, the influence of gravity force and air drag on the trajectory of a water droplet ejected under an angle, is less than the effect on the trajectory when the water droplet is initially placed horizontal, for distances till 3 mm. This is checked by the criteria of the smallest distance in vertical displacement between the trajectories of 1 m/s and 2 m/s. From the graph can be seen that this distance is the smallest for the 30° angle. The Reynolds number of the droplet \( (2 \text{ m/s, 30°}) \) after 6 mm travelling is (approximately) 4, so the regime for the drag coefficient is still valid.

Droplets travelling at higher velocities with initial direction in the negative y-direction (90° in respect to the x-axis), experience less influence from gravity (travelling in the same direction) and if there is no external air (force) acting on the droplet stream, the translation of the droplet stream in the x-direction is negligibly small. But due to the difference in drag force acting on the different droplets in the stream, the velocities for the droplets are changing. For the situation of a droplet stream with initially equally spaced droplets, this change in velocity can lead to a decrease or increase in spacing between the droplets, as can be seen in Figure 2.15. This effect will lead to instability at the beginning of a droplet stream, i.e. the droplets which are first ejected from the print head.
Figure 2.14  Trajectories of a water droplet ($d_d = 54 \mu m$) travelling through air. The different line styles, as shown in the legend, indicates the different initial velocities of the droplet. The timestep for the iterations $\Delta t = 0.1 \mu s$, the crosses represents 15000 iterations. The red, blue, green and black colour represent respectively an ejection angle of $0^\circ$, $10^\circ$, $20^\circ$ and $30^\circ$ with respect to the x-axis.

Figure 2.15  Situation of initially equally spaced droplets in a stream. Due to the difference in drag force, the velocity of the droplets changes and the spacing between the droplets is increasing or decreasing over the time. Image taken from [17].
The pressure of the medium (air) could also influence the droplets, because changing the pressure gives a change in density (assuming air behaves like an ideal gas and using the ideal gas law). This density change influences the acceleration (trajectory) of the droplet. Therefore, a simulation is done for droplets in air with a pressure of 1.0 bar\footnote{1 bar = \(10^5\) Pa}, 0.5 bar and 0.1 bar. The result is given in Figure 2.16. This simulation shows that the trajectories of the droplets under different pressures are the same for more than 10 mm. Because the distance between the DOD print head and CIJ stream is, normally, less than 10 mm, and due to the fact that the creation of low pressure in the experimental set-up is expensive, the pressure in the experiments is atmospheric.

2.6.3 Terminal velocity

After the droplet is released from the print head, the velocity of the droplet is changing under influence of the drag force and the gravitational acceleration. The velocity of the droplet when the drag force equals the gravitational acceleration force, \(\vec{F}_d = \vec{F}_g\), is called the terminal velocity

\[
g \frac{4}{3} \pi R_d^3 \rho_d = \frac{1}{2} \rho_{air} A_f C_D(Re) v_T^2 \Rightarrow v_T = \sqrt{\frac{8 g R_d \rho_d}{3 \rho_{air} C_D(Re)}}. \tag{2.48}
\]

After reaching the terminal velocity, the velocity of the droplet will remain constant. For example, a water droplet of \(d_d = 55 \mu m\) and \(v_d = 1.5 \text{ m/s}\) has \(v_T = 0.25 \text{ m/s}\) which gives \(Re_T = 0.91\), which leads that the drag coefficient for the droplet is now given by Equation 2.44.

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\footnote{1 bar = \(10^5\) Pa}
2.7 Simulations of moving droplets in a stream

Droplets in a stream behave different than just a single droplet moving in air. Air drag is acting on each droplet in this stream. If one of the droplets in this stream is colliding with an external droplet, this droplet is moving out of the stream, and the air drag force acting on this droplet is changing, but also the next droplet in the stream experiences a changing air drag force. Numerical simulations of cylinders and spheres in a stream are done, using Comsol Multiphysics 3.3a, to investigate this phenomenon.

2.7.1 2D simulations

In 2D simulations the droplets are simulated as solid cylinders. These cylinders have the same diameter as the droplets used in the experiments, and the distance between the cylinders is comparable with the distance between the droplets in the stream. The cylinders in the simulation are stationary and the air is moving with a constant velocity in the positive x-direction. For the simulations, one droplet is translated out of the stream, in the positive y-direction, as shown in Figure 2.17. When this droplet is translated a distance from the stream, the drag force acting onto the droplet will not only be parallel to the droplet stream, but separates into two components: the longitudinal component of the total drag force is called the drag force $F_{\text{drag}}$, the transversal-component is called the transversal reacting force $F_{\text{react}}$. This force is acting on the droplet in the direction opposite to the direction the droplet is translating, trying to force the droplet back into the stream. These forces are shown in Figure 2.18. Due to Newton’s third law, on the droplet at the position after the affected droplet in the stream, a force is acting in the opposite direction of the transversal reacting force. This principle is also shown in Figure 2.17. The simulations are done for translating one droplet different distances out of the stream and calculate the drag force and the transversal reacting force on each droplet in the stream. The results of the simulation of moving droplets with a velocity of 8 m/s, are given in appendix C.

Figure 2.17 2D simulation of the velocity field of droplet moving out of a droplet stream, due to a collision. The transversal reacting force is acting in the opposite direction of the movement of the moving droplet; on the droplet after the affected droplet also a force is acting, opposite to the transversal reacting force. The blue color represents a velocity of 8 m/s, the dark red represents 0 m/s.
In Figure 2.19 the drag force and transversal reacting force per unit length acting on the affected droplet (droplet 7) and the droplet after this affected droplet in the stream (droplet 8) as function of the translated distance are shown. The drag force depends on the velocity of the droplets (Equation 2.41), and so does the transversal reacting force. Therefore, the same simulation is done for droplets with a velocity of 11 m/s. These results are given in Figure 2.20.

Figure 2.19 2D simulation of the drag force per unit length and transversal reacting force per unit length acting on the affected droplet in the droplet stream (droplet 7) and the droplet after this affected droplet (droplet 8) as function of the translated distance of the affected droplet from the center of the droplet stream. In the simulation, the droplets are stationary and the air is moving with a velocity of 8 m/s. The diameter of the droplets is 100 µm and the distance between the droplets is 300 µm.
Figure 2.20 2D simulation of the drag force per unit length and transversal reacting force per unit length acting on the affected droplet in the droplet stream (droplet 7) and the droplet after this affected droplet (droplet 8) as function of the translated distance of the affected droplet from the center of the droplet stream. In the simulation, the droplets are stationary and the air is moving with a velocity of 11 m/s. The diameter of the droplets is 100 µm and the distance between the droplets is 300 µm.

From this 2D simulation, it can be seen that the drag force per unit length acting on the droplet is increasing when a droplet is translating out of the stream. Also, a transversal reacting force is acting on this translating droplet, forcing the droplet back into the droplet stream. Because these simulations are not valid for the 3D geometry, the transversal reacting force should be smaller, due to the fact that the air can flow more easily through the droplet stream and around the droplets, also simulations for the 3D geometry are done.

2.7.2 3D simulations

From the simulations in 2D, the drag force and transversal reacting force, acting on cylinders, are gained. Also simulations of moving spheres are done to find a relation between these forces and the translated distance from the stream. Because of the large computational resources required for the simulation, the simulation is done for four droplets in a stream, moving with a velocity of 8 m/s. Again the drag force and the transversal reacting force are measured on the moving droplet, as can be seen in Figure 2.21. The result of the drag force simulations is shown in Figure 2.22, the transversal reacting force is given in Figure 2.23. It can be seen that the transversal reacting force increases with an increasing distance, but after a maximum distance this force decreases again.

Now the transversal reacting force is given as a function of the distance the droplet is translated from its initial position in the stream, the y-component of the velocity of the droplet after the collision and its position can be calculated as function of the time, using the following equations.
with the boundary conditions

\[
\begin{align*}
  y(0) &= 0 \\
  v_y(0) &= v_0 = v_{A2,y},
\end{align*}
\]

(2.50)

where \( v_{A2,y} \) is the velocity-component in the y-direction of the droplet after the collision. The relation found between the drag force and the translated distance is

\[
F_{\text{drag}}(y^*) = 0.21 \cdot 10^{-6} + 0.07 \cdot 10^{-6} y^* + 0.11 \cdot 10^{-6} y^{*2},
\]

(2.51)

where \( y^* = \frac{y}{100 \cdot 10^{-6}} \), with \( y \) the distance of translation of the droplet. Increasing distance leads to an increasing drag force acting on the droplet. As the droplet is translated \( y > 115 \ \mu m \), the drag force acting on the droplet equals the drag force acting on a single sphere, the influence of the droplet stream onto the translated droplet then can be neglected and the droplet can be interpreted as free droplet (as comparison, the drag force on a single sphere with a diameter of 100 \( \mu m \), moving with 8 m/s through air is \( 4.6 \cdot 10^{-7} \) N, using Equation 2.41 and Table B 1).

The relation between the transversal reacting force and the distance, found by the simulations is

\[
F_{\text{react}}(y^*) = \begin{cases} 
-0.13 \cdot 10^{-7} y^* + 0.17 \cdot 10^{-7} y^{*2} & 0 \leq y^* \leq 0.6 \\
F_{\text{react}}(0.6) \cdot e^{-\frac{y^*-0.6}{0.12}} & y^* > 0.6
\end{cases}
\]

(2.52)
As can be seen in Figure 2.23, the relation is valid until a translation of 60 µm. When the distance increases, the transversal reacting force should go to 0 N, because then the translated droplet can be interpreted as a free droplet and on a free droplet only the drag force is acting. Within the limitations of the available computational resources, it was possible to calculate forces up to a translation of 60 µm. When the droplet is translated more than 60 µm out of the stream, the required number of mesh cells exceeded the available resources. The importance of the mesh cells can also be seen from the figure, where points are plotted for a different number of used mesh cells.

The deviation in points until a translation of 60 µm is small compared to the deviation in points for an increasing translation distance. Using this, again can be concluded the simulations represent the forces until a translation of 60 µm; a translation more than this distance should go to 0 N and an expected relation is given in Equation 2.52.

Now using Equation 2.52 and the relation between the drag force and the distance \( y \), the x-position and the velocity component in the x-direction of the affected droplet can be determined as function of the time, using

\[
\Delta F_{\text{drag}}(t) = F_{\text{drag}}(y(t)) - F_{\text{drag}}(0),
\]

\[\Delta a_x(t) = \frac{\Delta F_{\text{drag}}(t)}{m_d},\]

\[\Delta v_x(t) = \int_0^t \Delta a_x(t)\, dt.
\]
The trajectory of the droplet after the collision can now be determined. This is shown in Figure 2.24 for different velocities after the collision. These velocities are investigated, because these velocities are comparable with velocities found for the deflected droplets in the different experiments. The first four velocities in the figure (green to orange) are from the droplets with an initial velocity of 11 m/s, the black curve has an initial velocity of 8.5 m/s. The trajectories of the droplets show that after the collision, the transversal reacting force is acting in the direction back into the stream. This transversal reacting force is smaller than the drag force acting on the droplet (as can be seen in Figure 2.22 and Figure 2.23), so after the collision, the droplet will not move back into the direction of the droplet stream, but will keep moving away from the stream.
2.8 Boundary layer

When a droplet stream is generated out of the print head, a flow is created in the surrounding air. The air is in rest before the droplet stream is created, but a boundary layer flow appears, whose thickness will increase with increasing distance from the nozzle (orifice) [18]. The creation of this boundary layer on a continuous flat surface is already investigated; and is shown in Figure 2.25a and is given as function of the distance by [19]

\[
\delta_B(x) = \frac{2\beta}{\alpha} \sqrt{\frac{\mu_{air} x}{\rho_{air} U_0}} \approx 2 \sqrt{\frac{\mu_{air}}{\rho_{air} U_0}} \sqrt{x},
\]

(2.54)

where the subscript \(fs\) indicates the flat surface, \(\alpha\) and \(\beta\) are coefficients as given in Sakiadis [19] and \(U_0\) is the velocity where the flat plate is moving with. The continuous flat surface is in good approximation a continuous stream of droplets, with no spacing.
between them. Therefore, using this relation, the boundary layer as function of the
distance for a droplet stream out of a print head should be possible to determine. The
difficulty with the determination of the boundary layer on a droplet stream is that this
droplet stream is axisymmetric (so 3D and not 2D as the continuous flat surface) and
that there is a gap between the droplets, so air *entrainment* between the droplets is
possible. This entrainment means that air can flow between the droplets but is also
moved down with the droplet stream, so a virtual cylinder is created. The problem is
that this is not a complete cylinder, because there is momentum exchange between the
droplets, the air in the stream and the ambient air.

Therefore, first a moving cylinder is simulated. This simulation is done, by numerically
solving the boundary layer equations, which are, written in cylindrical coordinates [20]

\[
\begin{align*}
    \partial_t u + \partial_x u + \partial_r u &= \frac{1}{\rho} \left( \frac{1}{r} \partial_r (ru) + \partial_r^2 u \right), \\
    \partial_t (ur) + \partial_x (ur) + \partial_r (ur) &= 0,
\end{align*}
\]

and, mass conservation for a constant density flow with symmetry about the x-axis

\[
\begin{align*}
    \partial_x (ur) + \partial_r (vr) &= 0,
\end{align*}
\]

where \( u \) and \( v \) are respectively the x- and r-components of the velocity. The boundary
conditions are

\[
\begin{align*}
    u &= U_0, & v &= 0 & \text{at } r = 0, \\
    u &= 0 & \text{at } r \to \infty.
\end{align*}
\]

The complete solution for these equations can be found in Crane [21] or Glauert and
Lighthill [22].

The velocity in the boundary layer is increasing monotonously with increasing distance,
now the thickness of the boundary layer is defined as the r-value at which the velocity
in the x-direction is \( 0.90 \cdot U_0 \). This boundary layer is measured from the boundary of

![Figure 2.25](image-url)
the cylinder, so the radius of the cylinder is neglected in the boundary layer thickness. The result of the simulation of the moving cylinder, as well as the result from Equation 2.54, is plotted in Figure 2.26, from where the boundary layer as function of the displacement distance from the cylinder can be found

\[ \delta_{0.90, \text{cyl}} = 0.0048 \sqrt{x} \approx 3.5 \frac{\mu_{\text{air}}}{\rho_{\text{air}} U_0 \sqrt{x}}. \] (2.58)

This relation is in good approximation with the boundary layer thickness for a continuous cylindrical surface, found by Sakiadis [23],

\[ \delta_{\text{cyl}} = 4 \sqrt[4]{\frac{\mu_{\text{air}}}{\rho_{\text{air}} U_0}} \sqrt{x}. \] (2.59)

The difference in slope before the square roots can be explained by the fact that in the simulation the thickness at 90% of the velocity is taken and in the article the complete boundary layer.

Simulating the droplet stream is more difficult, because the droplets are not a cylinder, but air is between the droplets, so it is not a closed surface. Because these simulations, using a translating grid, are difficult, the simulations are done using stationary droplets in moving air. The difference with the simulation of the cylinder is, that the frame of axis is not stationary, which means that the center point \( x = 0 \) is translating with the air; this situation is given in Figure 2.25b. This also means that the development of the boundary layer is different in shape than the boundary layer on the continuous flat surface and cylinder.

Another effect what could occur is the creation of the so-called von Kármán vortex street. This phenomenon is shown in Figure 2.27. The wake (region immediately after a cylinder or droplet, which is also moving due to the flow) becomes unstable and
develops a slow oscillation in which the velocity and amplitude is periodic in distance and time. This oscillating wake will finally break up into two different vortices with opposite direction of rotation [18]. These von Kármán vortices will be created (for spheres) when Re > 200. Therefore, these vortices will not be of influence onto the droplet stream.

Simulations are done, using again the definition for the boundary layer as used for the cylinder. Also the thickness of the boundary layer is taken from the edge of the droplets, as can be seen in Figure 2.28. The relation found for the boundary layer thickness of the droplet stream as function of the displacement x, is

\[ \delta_{90,ds} = 0.0028 \sqrt{x} \approx 2.04 \frac{\mu_{air}}{p_{air}U_0} \frac{1}{\sqrt{x}}. \] (2.60)

As can be seen from Figure 2.26 and using Equations 2.54 and 2.60, the boundary layer thickness on the continuous flat surface and on the droplet stream differ a little which can explained by the fact that the droplet stream is not a closed surface, but air in trapped between the droplets. This can lead to some small vortices between the droplets, which has also influence on the thickness of the boundary layer.

It can be concluded that the Reynolds number is important for the boundary layer around the stream: for 1 < Re < 200, the boundary layer on the surface of a droplet stream is given as Equation 2.54, for higher Reynolds numbers, this relation is not allowed anymore, because other vortices can be created between the droplets in the stream, so these also can influence the boundary layer. This simulation needs more mesh cells and this was not available within the computational resources.

![Example of 2D von Kármán vortex street. The wake behind a cylinder becomes unstable and develops a slow oscillation in which the velocity is periodic in time and distance, as well as in increasing amplitude. Image taken from [24].](image)

### 2.8.1 Results of simulations

From the simulations, 2D and 3D, done for a droplet stream, it can be concluded that when one droplet is translated from this stream, the drag force and transversal reacting force are acting on this droplet, but also on the next droplet in the stream (neighbour droplet of the affected droplet) the forces are changing. But, once a droplet is translated out of the stream, it will not move back into the direction of the stream, but it moves away further from the stream.

Also is seen that a boundary layer is created on the boundary of the droplet stream, and that the relation between the thickness of this layer and the displaced distance from the droplet stream is the same as the relation for the boundary layer on a continuous flat surface. This is valid for the geometry used in these simulations.
Other forces acting on a droplet

A lot of forces act on a droplet, when it is moving in air, in a stream or after a collision, as discussed in the paragraphs before. The main forces are the drag force, gravitational force and the transversal reacting force. But also other forces act on droplets, but have less influence, due to the small diameter of the droplets.

2.9.1 Saffman lift force

Droplets in a stream can rotate, due to their internal circulations. Assume that the droplets are stationary translating in the stream (with no rotation). When a droplet is brought out of the stream into a shear layer, it develops a net rotation. Due to this rotation, the droplet experiences a transverse force, which is called the Saffman lift force, is given by

\[ \vec{F}_{Saff} = 1.61 \mu_{air} d_d \bar{u}_{rel} \sqrt{Re_G}, \]

where \( Re_G = \frac{\rho_{air} d_d^2}{\mu_{air}} \frac{du}{dy} \ll 1 \) is the condition. For the droplets in the stream, when the condition satisfied, the Saffman lift force is in the same order as the transversal reacting force (~ \( 2.6 \times 10^{-8} \sqrt{Re_G} N \approx F_{react} \)). But for the situation described in this project, the criterion \( Re_G \ll 1 \) is not satisfied, so it is unknown if this force is important. Also in the simulations, the droplets were stationary, so rotation was not possible. The Saffman force could influence the droplets when one droplet is translated out of the stream. This force should be taken into account in further studies to this subject, because, if the condition for \( Re_G \) is satisfied, the Saffman force can be important as well.

Figure 2.28 Simulation of boundary layer on droplet stream. The simulation is 3D, this is the x-y view, shown is the velocity field, where red is 8 m/s, and blue 0 m/s.
3 Experimental set-up

In this chapter the print heads are described which are used to generate the droplets. After this, a complete overview of the used experimental set-up is given. Because the results are dependent on the pictures made during the experiments, the resolution of the cameras is discussed, as well as the illumination of the droplets. The analysis method of the pictures is discussed briefly. At the end of the chapter, the properties of the liquids, used for the droplets, are given.

3.1 Print heads

To deflect droplets from a stream, two print heads are used: a continuous ink jet (CIJ) and a drop on demand (DOD) print head. The operating principle of these print heads is given in the next paragraphs.

3.1.1 Continuous Ink Jet (CIJ)

The CIJ print head is a print head where the liquid, under high pressure, is brought in a reservoir in the print head. The pump, which controls the flow, pumps the liquid into the reservoir, where the liquid is driven through a nozzle (with a diameter of 50 µm), and will break up into a continuous stream of separate droplets, with uniform size and separation. Due to an electrically driven piezo translator, the distance between the droplets after break up can be controlled. Adjusting the amplitude of the sinusoidal signal to the piezo translator, the distance between the droplets after break up can be increased or decreased. The print head is schematically shown in Figure 3.1.

When a liquid is pushed through an orifice, the liquid jet will spontaneously break up into small droplets, due to disturbances on the surface of the jet [2]. Using a CIJ print head with the piezo translator, the break up process in the jet can be controlled to get a stable droplet stream. The difference of this print head (TNO patented) with a normal CIJ print head, is that this print head can print liquids of high viscosity (up to 500 mPa s) at frequencies up to 140 kHz. The print head in the experiments operates at a frequency of 20 kHz, using a nozzle with a diameter of 50 µm.

3.1.2 Drop on Demand (DOD)

The DOD print head can be used for the printing of droplets on demand. The schematic overview is given in Figure 3.2. In the DOD print head an electric signal deforms a piezo-electric membrane, which generates a pressure pulse, which ejects a liquid drop...
through the glass capillary. Adjusting the height of the liquid reservoir before the inlet, the pressure in the reservoir in the DOD print head is set. Adjusting the pulse to the piezo translator, the moment of ejecting the droplet can be controlled. The advantage of a DOD print head is that a single droplet can be printed at a controlled moment. The print head, used for the experiments is the MicroFab MJ-AT print head with the diameter of the glass capillary of 50 µm.

Figure 3.2  a) Schematic overview of DOD print head, b) the inner of the DOD print head. Picture taken from MicroFab Technologies website (http://www.microfab.com).

3.2 Complete set-up

The complete experimental set-up is discussed in the next section. First, the set-up to generate the droplets is discussed, after that an overview of the electrical components in the experimental set-up is given.

3.2.1 Pumping and printing system

To get an impression of the generation of the droplets in the CIJ print head and to follow the liquid through the pumping system, Figure 3.3 is drawn. The highly viscous liquid used in the CIJ is pumped from a reservoir through a flow controlled pump (Separations). The liquid is pumped through a 7 µm stainless steel filter (Swagelok, SS-4FW4-7). This filter removes particles from the liquid, which are larger than 7 µm in diameter and which can clog the nozzle of the print head. The pump is pumping with mechanical pulses. This gives pulsations into the liquid, which influences the stability of the droplet stream. Therefore, a damper is used to remove the pulsations from the liquid. This damper, which works optimal at a pressure of 80-100 bar, is pressure controlled using an adjustable valve (Swagelok, SS-4R3A) and a pressure gauge (Swagelok, PGI-100C-PG6000). Now, the liquid flows into the reservoir of the CIJ print head. The collisions of the droplets in the generated droplet stream with the droplets from the DOD print head are recorded using two cameras (uEye, UI-2240m): one camera (camera 1) perpendicular on the collision, the other camera (camera 2) is in the line of sight with the DOD print head. Both cameras are illuminated with a LED.

3.2.2 Electrical components

A schematic overview of the complete experimental set-up is given in Figure 3.4. The function generator (TTi, TG215) creates a sine wave with a frequency of 20 kHz. The function generator creates a voltage (with a maximum amplitude of 10V), but cannot produce enough power. Therefore, the signal is send to an amplifier (PI, LVPZT). The amplified signal (with a maximum of 100 V) drives the piezo translator of the CIJ print head (PI, P-840.20).
The pulse divider receives a TTL signal from the function generator (a detailed description of the TTL signal is given in appendix D). The signals which drive the piezòs of the print heads should be synchronized to view the droplets of both print heads at the same time. Due to the fact the CIJ is printing at a frequency of 20 kHz and the maximum possible stable printing frequency, experimentally found in this project, of the DOD print head is much lower (500 Hz); the pulse to the CIJ should be divided to make this synchronization possible.

The output signal of the pulse divider is a TTL signal as well. The pulse divider (74HCT4040) uses a binary counter to divide the frequency of the signal with some specific factor (in the experiments this factor is 64). The output signal is the trigger pulse for the Arbitrary Waveform Generator (AWG).

Figure 3.3  Schematic overview of the pumping and printing system. The highly viscous liquid is pumped from the reservoir through a filter. The damper removes the pulsations of the pump. The pressure in the damper is controlled using an adjustable valve. Then, the liquid can be printed. The two cameras, which are illuminated using LEDs, record the collision.
The AWG (Agilent 33220A) receives the trigger from the divider. To generate drops with the DOD, a pulse should be send to the piezo of the DOD. The shape of the waveform is given in Figure 3.5. The parameters of this waveform are important, like decreasing the dwell time creates smaller droplets. Because the AWG cannot deliver enough power, the signal is send to another amplifier, which amplifies the voltage of the signal, again, with a factor 10. The DOD print head is mounted on a micrometer stage (Owis, MT-60S-25-XYZ-MS), which enables the possibility to translate the print head on micrometer-scale relative to the CIJ stream.

The two cameras, which are both mounted on the same XYZ-precision stage (Owis, LT-60-25), display the droplets from the CIJ and DOD onto the screen and should be synchronized. The cameras get a trigger pulse from the AWG, but this pulse is first send to a pulse generator to delay this pulse, wherefore the complete trajectory of the droplets before and after the collision can be viewed. At the computer, the initial delay and final delay of this pulse, is adjusted. Now, both cameras work the same, and at the moment a camera receives the trigger pulse, it starts the time for ‘waiting’ until the delay. At the moment the picture should been taken, it ‘opens’ its shutter and creates a flash output. A way to interpret this output is given in Figure 3.6. When the circuit is closed, a potential difference of 10 V over the resistance is created and an output pulse is created. This output pulse (flash out) is a trigger for a Schmitt-trigger (74HCT14). The flash output is not a smooth pulse, but contains noise. Therefore, this Schmitt-trigger condition the signal; when the input is higher than a certain threshold, the output

Figure 3.4 Schematic overview of the experimental set-up. Both cameras are connected to a computer, which send a trigger pulse to the cameras at the moment the picture should be made.
is high, when the input is lower, the output is low. The output of the Schmitt-trigger is
the input for a D-Flip-flop (74HCT74). The function of this flip-flop is to synchronize
the flash out pulse with the 20 kHz signal of the function generator, so the CIJ and the
DOD are synchronized. This flip-flop output signal is high; when there is an input from
the Schmitt-trigger, the signal resets to low, and at the next clock pulse, the signal is
high again. These pulses now can be used to enlighten the LED. For each camera, the
flash out pulse (the pulse which is synchronized on the DOD pulse) and the 20 kHz are
synchronized, but these synchronizations can differ for both cameras, due to the
processing time of the camera on the computer trigger (or vice versa). To prevent the
fact that an LED is not on when a cameras shutter is open, an OR-gate (74HCT32) is
used for both signals. The output signal of this OR-gate is the trigger input for a pulse
generator (TTi, TGP110). Because this trigger pulse is (about) 50 µs, the pulse
generator decreases the duration to 1 µs. Again, the pulse generator is not able to
generate enough power, so the signal is amplified using a MOSFET and a power
supply. In this way a high current through the LEDs can be generated. The pictures of
set-up are shown in Figure D 2 -Figure D 4.

Figure 3.5 Waveform with pulse length of 28.5 ms is send to the piezo of the DOD. An increase in frequency
of the waveform shortens the pulse lengths. For example, for 25 ms, the first square pulse length
(dwell time) is 60 µs, the second square pulse length (echo time) is 150 µs (terms dwell and echo
taken from the MJ-AT user’s manual, MicroFab Technologies, Inc).

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the input for a D-Flip-flop (74HCT74). The function of this flip-flop is to synchronize
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generate enough power, so the signal is amplified using a MOSFET and a power
supply. In this way a high current through the LEDs can be generated. The pictures of
set-up are shown in Figure D 2 -Figure D 4.

Figure 3.6 Schematic overview of the flash output. When the camera gives the output, the circuit is closed
and there is a potential difference of 10V over the resistance. This pulse is a trigger pulse for
the Schmitt-trigger.
3.3 Resolution of the cameras

Because all the measurements of the droplets are done using pictures made by CCD cameras, it is important to know the resolution of the pictures. The cameras (uEye, UI-2240m) uses Navitar lenses, which can zoom 12 times. For determination of the resolution, a picture is made at the minimum zoom and at the maximum zoom, using a Multi-Grid Standard Stage Micrometer (Edmund Optics, NT58-607). Using the pictures from Figure 3.7, the resolution can be determined. The resolution is also dependent on the distance from the camera to the droplet stream (as can be seen in appendix D). Therefore, this distance is constant for all the experiments and is 5.1 cm. For the minimum zoom at this distance, the resolution is 2.73 µm/pixel, for the maximum zoom the resolution is 0.227 µm/pixel.

3.4 Light sources

The droplets in the stream are illuminated and pictures of the shadows of the droplets are made. The shadows are obtained, when the light parallel to the optical axis illuminates the droplets from the background, so the LED is placed behind the droplet stream and illuminates the camera [26].

The illumination of the droplets is stroboscopic; a small area of the droplet stream is shortly illuminated, which is synchronous with the frequency of the droplets, and a sharp image of the droplets is obtained. Because the droplets are translating at high frequency, the light used for the illumination should have a short pulse (a pulse length of 1 µs gives raise to a motion blur of $8.5 \text{ m/s} \cdot 1 \mu \text{s} = 8.5 \mu \text{m}$). Therefore, a red PowerLED (Lumiled Luxeon Star hex) with a lens (Luxeon Star clear), is used to collimate the light of the LED, is a good light source, but also ‘Pulsed Xenon Flashpac’ works. This Flashpac (Perkin Elmer, LS-1102-2) is a high voltage discharge flash bulb, with a pulse length of 2 µs (so a motion blur of 17 µm).

The light source should also have enough power to illuminate the droplet when the camera zooms onto one droplet. Tests are done and the results are given in Figure 3.8. As can be seen from the figure, some motion blur is in the picture; this can be seen that the height of the droplet is a few pixels more than the width of the droplets. As also can be seen from the figure, both the Flashpac and the PowerLED can be used to illuminate one droplet in the stream. The advantage of the Flashpac is that this light source should not be placed close to the droplet stream, but has a long working distance. The disadvantage of this light source is, because it is a discharge bulb, it has a short life time.

![Figure 3.7](image)

Figure 3.7 Pictures from the Multi-Grid stage micrometer. a) minimum zoom of the camera, b) maximum zoom. 1 division of the grid is 100 µm.
(only 10000 pulses). Therefore, and because the experiment uses two cameras, the PowerLED is used. The specifications are given in Table 3.1.

Table 3.1 Specifications of the red PowerLED

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>617 nm</td>
</tr>
<tr>
<td>Typical luminous flux</td>
<td>55 lm</td>
</tr>
<tr>
<td>Maximum voltage</td>
<td>3.51 V</td>
</tr>
<tr>
<td>Maximum current</td>
<td>350 mA</td>
</tr>
<tr>
<td>Pulse length to LED</td>
<td>1.9 µs</td>
</tr>
</tbody>
</table>

Figure 3.8 Comparison of the PowerLED and the Flashpac (nanolight) analyses of one droplet using Matlab. For b), c) and d) an extra lens is used in front of the light source, where the focal length is given as well. In e) the LED is at a distance of 1.8 cm from the droplet stream. The distance between the Flashpac and the droplet stream is 10 cm.

3.5 Analysing pictures

The analysis of the pictures is done using MathWorks Matlab (version R2006b). A routine is written to determine the diameter and position of the droplets. An example of a typical analysis of a picture is shown in Figure 3.9. From the manipulated picture, the area of the droplets is known, and using the pixel resolution, the size of the droplets is determined. Also, from this area, the center of the droplet can be determined, so the position of the droplet is known. Using this position, the trajectories of the droplets can be determined. Calculating the distance from two neighbouring droplets, the velocity of the droplets is also determined.
3.6 Materials

The aim of the project is on one hand to investigate the feasibility of colliding droplets as deflection method. Because the liquids used for printing are highly viscous, a highly viscous material is needed for the experiment. After the collision the two droplets should be collected and recycled, so therefore these two liquids should not merge. Because the CIJ print head used in the experiment should also be used for other liquids, the highly viscous material should be soluble in water. Therefore, the liquid used in the CIJ print head is: tri-ethylene glycol. For the stability measurements, which will be described in Section 4.1.1, isopropyl alcohol is used. Both liquids are described in the next paragraphs. In the DOD print head demi-water is used. This, because the DOD print head is fragile and sensitive for small particles. Demi-water is clean, and using this liquid, it is not possible that particles in this liquid will deposit in the glass capillary of the print head.

3.6.1 Isopropyl alcohol (IPA)

Isopropyl alcohol (IPA), or isopropanol, is the common name for 2-propanol. The chemical formula is C₃H₈O. The liquid is colorless, flammable and volatile. Therefore, this liquid can be used for cleaning electronics, surfaces and computer monitors. IPA is also solvable in water. Its properties, like viscosity, surface tension and density, are given in Table 3.2.

3.6.2 Tri-ethylene glycol

Tri-ethylene glycol is a colorless, odorless liquid, which is often used as plasticizer. It is also often used in commercial air sanitizers, like Ambi Pur® and Breeze®. The chemical formula is C₆H₁₆O₄ (or in structural formula HO-CH₂-CH₂-(O-CH₂-CH₂)₂-OH). The viscosity and surface tension of the liquid are measured, using a rheometer to measure the shear stress in the liquid and using this stress to determine the viscosity of the liquid. This is also given in Table 3.2.
Table 3.2 Properties of IPA, tri-ethylene glycol and demi-water. The values for surface tension and density of IPA and demi-water are taken from [27]. All values valid at room temperature, 25°C.

<table>
<thead>
<tr>
<th></th>
<th>IPA</th>
<th>Tri-ethylene glycol</th>
<th>Demi-water</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Viscosity</td>
<td>2.04 mPa s</td>
<td>38.8 mPa s</td>
</tr>
<tr>
<td></td>
<td>Surface tension</td>
<td>20.9 mN/m</td>
<td>42.5 mN/m</td>
</tr>
<tr>
<td></td>
<td>Density</td>
<td>$0.785 \cdot 10^3$ kg/m$^3$</td>
<td>$1.124 \cdot 10^3$ kg/m$^3$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4 Experimental results

For the investigation of the deflection of a droplet from a droplet stream using a collision with another droplet, first the stability of the print heads is investigated. If the print heads are printing stable, the air influence on the droplets can be investigated. After that, the experiments with colliding droplets can be done, varying impact parameters and velocity, and these results can be compared with the experiment done by others [7] - [10]. At the end, the range is investigated where the deflection of the droplet is at least 2°, so the collisions between droplets can be used for deflection. The results of those investigations are given in the next sections.

4.1 Stability of the print heads

For the collision process, both the CIJ print head and the DOD print head should operate in a stable manner. Therefore, first the stability of the CIJ is investigated, then the stability of the DOD.

4.1.1 Stability of the CIJ print head

The stability of the printing process is a crucial factor for the collisions. When the droplet stream is not stable, it is not possible to intercept the droplets with the predetermined impact parameter. The stability is analyzed experimentally, by making images and analyze the droplet position variations during time. To prevent the influence of an external air stream on the droplet stream, a transparent PVC box is build around the set-up. This experiment for the CIJ is done during 15 minutes, making 5 pictures per second of the droplets at one constant camera position. The results for IPA and tri-ethylene glycol are shown in Figure 4.1. For the measurements of IPA, the vertical deviation in position is 0.5 droplet diameter, for the tri-ethylene glycol this deviation is 1 droplet diameter (100 µm). The horizontal deviation of the droplet is negligibly small. For more viscous liquids, the flow from the pump should be 1.0 mL/min and the pressure on the damper in the range 80 – 100 bar. The pump is very important in this set-up, because this pump causes the deviation in the droplet positions, due to the mechanical pulsations. Learned from this experiment is that the printing process is stable during a few minutes, and that there is a deviation of 1 droplet diameter, during longer time.

4.1.1.1 Distance between the droplets

For the stability of the droplet stream, also the distance between the droplets, at different positions in the stream, is investigated. The distance between the droplets could increase or decrease, as explained in paragraph 2.6.2, which could influence the impact parameter. The result of this stability experiment is given in Figure 4.2. The different positions show that the distance between the droplets in the IPA stream decrease at a distance of 30 mm under the nozzle plate. The distance between the tri-ethylene glycol droplets decreases (and so increases as well) already at 15 mm under the nozzle plate. This means, that the collisions should be done as close to the nozzle as possible, because there the droplet stream is most stable. This also means that this effect is a general effect (see also Leichtberg et al. [17]), which (probably) also occurs in other printing projects (at TNO). Therefore, my recommendation is to check this effect in other projects as well, by analyzing the droplet stream at larger distances under the nozzle plate, and making pictures for a longer period of printing time.
4.1.1.2 Other materials

For the stability other materials are investigated as well. Ethylene glycol and di-ethylene glycol are used, because these liquids are more viscous than water or IPA, respectively 15.7 mPa s and 24.7 mPa s, and the surface tension is comparable with the surface tension of tri-ethylene glycol (47.4 mN/m and 44.5 mN/m resp.), so these liquids can be compared with the results of tri-ethylene glycol. The droplets appear to translate vertically through the stream, so the droplet positions differ in time so these liquids were not stable enough to use for the collisions. This, and the fact that tri-ethylene glycol is the most viscous; this liquid is the best for using in this experiment. Also mixtures of glycerol–water are investigated, but nozzle problems occur using these mixtures; the nozzle was clogged, due to the stickiness of the mixtures and particles in the mixtures. Filtering the mixture before pumping had a negative influence onto the liquid: the plastic filter appeared to contaminate the liquid, which lead to a decrease in surface tension. Therefore, also these mixtures were not usable. Another problem with these mixtures was the stability of the droplet stream. When the mass ratios are higher (i.e. more glycerol is used in the mixture), the viscosity of the mixture also increases, but these mixtures could not be printed in a stable manner. Therefore, the tri-ethylene glycol was the most stable, high viscous liquid.

4.1.2 Stability DOD

The stability of the DOD droplets is also important for the collisions. The DOD droplets are smaller in volume and the velocity of the droplets is much lower, so the air drag has a stronger influence on the trajectories of the DOD droplets (already discussed in section 2.6). Therefore, the stability of the droplets is investigated, as well as the influence of the boundary layer on the CIJ droplet stream onto the DOD droplets. The result is given in Figure 4.3. In this figure the position of the droplet is shown at four different positions in its trajectory, at different distances next to the CIJ droplet stream.
(CIJ print head is printing during the measurement and the droplet velocities are 8.8 m/s).

Figure 4.2 Stability of distance between the droplets. Three different positions are shown: first is 0.5 mm under nozzle plate, the middle 15 mm under the nozzle plate and the last is 30 mm under the nozzle plate of the CIJ print head. The colored arrows represent the distances between the droplets; equal colors represent equal distances. The flow for both liquids is 1.0 mL/min, the pressure on the damper is for IPA 100 bar and for tri-ethylene glycol 80 bar. The diameter of the droplets in both experiments is 100 µm. The stream is not perfectly vertical, due to the fact that the CCD camera was mounted slightly tilted on the lens.
The DOD droplet is deflected from its original trajectory, due to the presence of the CIJ stream. The positions of the CIJ droplets are also plotted, as well as the diameter of these droplets, to illustrate the position of the DOD droplets relative to the CIJ droplets. The trajectory from the droplets which are undisturbed (no CIJ stream present) are plotted as well. When the DOD droplet is close to the CIJ stream, the DOD droplet is deflected. At a distance of 1 mm from the CIJ stream, the trajectory of the DOD is not disturbed anymore. This means that the boundary layer on the CIJ stream has a thickness in the order of 1 mm. Comparing this thickness with the thickness found with Equation 2.60, this theoretical value gives a thickness of 0.26 mm. This difference could be explained by the fact that the distance between the CIJ droplets in the stream in the experiment is three droplet diameters and in the simulation only two droplet diameters. Also is it possible the DOD print head was oscillating after the change in position. The DOD is placed in a holder and a tube was used to connect the print head to the water reservoir. This tube was stiff and during the change of position of the DOD print head this tube was hindered by the experimental set-up. This effect could bring the oscillation into the print head, which leads to a small shift in trajectory at positions where the boundary layer, maybe, has no influence anymore. Most of the time, the tube was not a problem at all.

Also the distance from the glass capillary of the DOD print head to the CIJ droplet stream is important; if this distance is too large, the DOD droplets already starts to deflect due to gravity, which also can be seen in Figure 2.14.

From Figure 4.3 can also be seen that the stability of the DOD droplet is good. This can be seen from the fact that the errorbars, which represents the standard deviation in x- and y-position are small and equal in size. Because the pictures were very bright, it is hard for Matlab to find the boundaries of the droplets, so the size of the droplets is not always constant (it differs a few pixels), which gives a small deviation in center of the droplet, as can be seen from the figure.
4.2 Collisions of the droplets

After the stability of both droplet streams has been investigated and the velocity, volume and distance between the droplets can be controlled, experiments of collisions between droplets can be performed. Three experiments are done where the position of the DOD print head is translated along the x-axis, as shown in Figure 4.4, from a collision at the center of the CIJ droplet, to the boundary of the droplet. For the measurements four positions in the trajectory of the DOD droplet are analysed, two before the collision, two after the collision, using the delay of the trigger pulse to the cameras (see Section 3.2).

![Figure 4.3](image-url) Stability of a DOD water droplet \(d_{\text{DOD}} = 55 \mu\text{m}, v_{\text{DOD}} = 1.5 \text{ m/s}\) at different positions next to the CIJ droplet stream \(d_{\text{CIJ}} = 100 \mu\text{m}, v_{\text{CIJ}} = 8.8 \text{ m/s}\). The four positions are determined using a delay at four constant times: \(t = 0\) s, \(t = 50\) µs, \(t = 150\) µs and \(t = 330\) µs. The standard deviation in x- and y-direction is given as well, as well as the diameter of the CIJ droplets (black dashed lines). The trajectory of the undisturbed DOD droplet is given by the red line. Especially from the deviation from DOD position to the undisturbed line the deflection is determined. Position of the camera is 9 mm under the nozzle plate of the CIJ. The distance from the DOD nozzle to the CIJ stream is 2.2 mm.

![Figure 4.4](image-url) Top view (in negative z-axis) of the experimental initial position of the DOD and the CIJ print head. The DOD is translated in the x-direction The y- and z-positions are constant during the complete set of experiments.
To analyse the results of the experiment, pictures are taken with both cameras. Especially the outcome of the collision is important. To compare the results of the experiment with the experiments done by others, the Weber number of the collision is important, as well as the impact parameter. The impact parameter is determined by Equation 2.25.

The Weber number, as given in Equation 2.4, is valid for droplets of the same liquid. Because the collisions from the experiments are done using tri-ethylene glycol and water, which gives normally two Weber numbers, the ratios of the densities, surface tensions and diameters are important as well,

\[
\frac{\rho_{\text{TEG}}}{\rho_w} = \frac{1.124 \cdot 10^3}{0.998 \cdot 10^3} \approx 1, \quad (4.1a)
\]

\[
\frac{d_{\text{TEG}}}{d_w} = \frac{110 \cdot 10^{-6}}{55 \cdot 10^{-6}} = 2, \quad (4.1b)
\]

\[
\frac{\sigma_{\text{TEG}}}{\sigma_w} = \frac{42.5 \cdot 10^{-3}}{72.8 \cdot 10^{-3}} \approx \frac{1}{2}, \quad (4.1c)
\]

where the subscript TEG is the abbreviation of tri-ethylene glycol, and the values from Table 3.2 are used. The coalescence or stretching separation as result of the collision is determined by the strength of the liquid ‘bridge’ formed after the collision, and this bridge is as strong as the surface tension of the weakest liquid. Therefore, for the collisions one Weber number is defined, using the properties of the droplet with the lowest surface tension,

\[
\text{We} = \frac{\rho_{\text{TEG}} d_{\text{TEG}} u_{\text{rel}}^2}{\sigma_{\text{TEG}}}. \quad (4.2)
\]

From the pictures, three regimes are found: bouncing, stretching separation and coalescence. Examples of all regimes are shown in Figure 4.5. The results of the collisions with higher impact parameters are most of the time bouncings. In a) this regime is shown. After the collision the DOD droplet continues its initial trajectory with a small deflection. Its diameter remains constant. In b) it can be seen that the volume of the DOD droplet decreases and a small satellite droplet is created. Therefore, this outcome is comparable with stretching separation, as shown in Figure 2.8. The DOD droplet also bounces back into the direction of its original trajectory before the collision. This is not always in the stretching separation regime, sometimes the DOD droplet is deflected a little from its original trajectory, but it always decreases in volume. The third regime is coalescence. This series is shown in the figure in c). In these experiments, both cameras were recording images, but camera 2 (see Figure 3.3) only showed the deflection of the droplets, where the deflected droplets appears bigger than the other droplets, which means the deflection is in the direction parallel to the optical axis of the camera. Also, this camera is used for determination of the z-position of the DOD droplet during the collision.

Four experiments are performed for different Weber numbers and impact parameters. Three of the experiments are described by Figure 4.4, the forth experiment is performed by changing the position in z-direction, and keeping the positions in x- and y-direction constant. The important parameters of the experiments are given in Table 4.1. The results of the experiments with the changing x-position are shown in Figure 4.6. Also
the theoretical curves for the prediction of bouncing, stretching separation and coalescence, as found in Estrade [8], are shown.

Table 4.1 Parameters of the droplets in the experiments

<table>
<thead>
<tr>
<th>Serie 1</th>
<th>CIJ</th>
<th>DOD</th>
<th>Serie 2</th>
<th>CIJ</th>
<th>DOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity [m/s]</td>
<td>8.6</td>
<td>1.3</td>
<td>8.4</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Diameter [m]</td>
<td>$110 \cdot 10^{-6}$</td>
<td>$55 \cdot 10^{-6}$</td>
<td>$110 \cdot 10^{-6}$</td>
<td>$55 \cdot 10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>Volume [L]</td>
<td>$7.0 \cdot 10^{-10}$</td>
<td>$0.87 \cdot 10^{-10}$</td>
<td>$7.0 \cdot 10^{-10}$</td>
<td>$0.87 \cdot 10^{-10}$</td>
<td></td>
</tr>
<tr>
<td>Distance droplets CIJ [m]</td>
<td>$330 \cdot 10^{-6}$</td>
<td>$275 \cdot 10^{-6}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distance DOD-CIJ [mm]</td>
<td>3</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Serie 3</th>
<th>Serie 4</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity [m/s]</td>
<td>11.0</td>
<td>1.6</td>
<td>9.6</td>
</tr>
<tr>
<td>Diameter [m]</td>
<td>$110 \cdot 10^{-6}$</td>
<td>$55 \cdot 10^{-6}$</td>
<td>$130 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>Volume [L]</td>
<td>$7.0 \cdot 10^{-10}$</td>
<td>$0.87 \cdot 10^{-10}$</td>
<td>$11.5 \cdot 10^{-10}$</td>
</tr>
<tr>
<td>Distance droplets CIJ [m]</td>
<td>$440 \cdot 10^{-6}$</td>
<td>$325 \cdot 10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>Distance DOD-CIJ [mm]</td>
<td>4</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

*** $1 \text{ L} = 1 \cdot 10^{-3}\text{ m}^3$
Figure 4.5  Three outcome regimes after the collision between a water droplet ($d_{DOD} = 55 \, \mu m$, $v_{DOD} = 1.5 \, m/s$) and a tri-ethylene glycol droplet ($d_{TEG} = 110 \, \mu m$, $v_{TEG} = 8.8 \, m/s$). a) bouncing, $I = 0.93$, b) stretching separation, where the water droplet decreases in volume, $I = 0.67$, c) coalescence, $I = 0.14$. The pictures are taken at four different times in the trajectory of the DOD droplet, $t = 0 \, \mu s$, $t = 190 \, \mu s$, $t = 510 \, \mu s$ and $t = 690 \, \mu s$. 
Figure 4.6  The impact parameter as function of the Weber number for three different experiments, where y- and z-position are constant and the x-position is changed. The diameter ratio $\Delta = 0.5$. The bouncing and separation curve are taken from Estrade [8], the red dashed predicts the stretching separation and the yellow dashes the bouncings. Both are found in the experiments.

From the figure it can be seen that the three series where changing the x-position of the DOD relative to the CIJ stream are in good agreement with the theoretical curves. The red and yellow dashes give a better representation, but because only these three Weber number are investigated, the complete curve could not be drawn.

In Figure 4.7 the results are shown for all experiments. From the figure can be seen that the results from the experiments with the changing z-position (serie 4) does not agree with the theoretical curves and with the other experiments. From this experiment, almost all the results of the collisions are coalescence, where, as can be seen from the other experiments, also other results are expected. The difficulty for this experiment is the stability of the CIJ stream; collisions of the DOD droplets occur with other droplets than the ‘target droplet’. Also, after the collision both droplets are deflected vertically upward or downward, so the droplets coalesce with the next (neighboring) droplet in the droplet stream.

From Figure 4.6 and Figure 4.7 the conclusion can be drawn that, for these experiments, where the two droplets are not the same liquid, the results of the experiments with changing x-position agree with the experiments done by others with droplets of the same liquid. The experiments with changing z-position do not agree, due to the instability and deflections.
4.2.1 Comparison with the theory

Using the equations for the determination of the velocities of the droplets, as explained in Section 2.5, the theoretical values of the collisions can be compared with the experimental, using the pictures of the collisions.

In appendix E, the theoretical and experimental velocities found for the bouncing and stretching separation collisions are given. For the stretching separation regime, the elasticity number is calculated for the collision, using the diameter of the DOD droplets before and after the collision. The diameter of this droplet decreases, so does its mass. The velocities for the coalescence regime are given in Table E 4.

As can be seen from Table E 1 - Table E 3, the velocities found from the experiments are different from the theoretical calculated velocities. The velocities of the CIJ droplets for bouncing do not vary very much, the velocities for the DOD droplets in the bouncing regimes and the velocities from both droplets in the stretching separation regime differ a lot. This can be explained by the fact that there is not only mass transfer from one droplet to other. From the pictures can be learned that the diameter of the DOD droplet decreases from 55 µm to (about) 45 µm, but the diameter of the CIJ droplet increases not with the same volume, the DOD droplet looses. Also the satellite droplets that are created do not have this volume. Therefore, there must be other causes for the kinetic energy loss after the collision.

4.2.2 Energies

In a completely inelastic collision, the total kinetic energy is not conserved. But in the regimes of stretching separation and bouncing, the collisions are elastic or not completely elastic (the elasticity number $0 < \lambda < 1$). In these collisions the energy should be conserved. As already can be seen from upper paragraphs, there is a loss in...
kinetic energy after the collision, so a part of the kinetic energy is converted into other energies, which should explain this energy loss. Therefore, a new relation should be introduced, for which the following relation is valid,

\[ E_{\text{kin},1} = E_{\text{kin},2} + E_{\text{str}} + E_{\text{vibr}} + E_{\text{heat}} + E_{\text{surf}} + E_{\text{rot}} + \ldots \] (4.3)

where \( E_{\text{kin}} \) is the kinetic energy, \( E_{\text{str}} \) the stretching energy, \( E_{\text{vibr}} \) the vibration energy, \( E_{\text{heat}} \) the heat energy, \( E_{\text{surf}} \) the surface tension energy and \( E_{\text{rot}} \) the rotation energy. This gives for the energy loss in kinetic energy

\[ \varepsilon E_{\text{kin},1} = E_{\text{kin},2}, \quad \frac{m_{A2}}{m_{A2} + m_{B2}} < \varepsilon < 1. \] (4.4)

For the situation \( \varepsilon = 1 \), the collision is completely elastic and for \( \varepsilon = \frac{m_{A2}}{m_{A2} + m_{B2}} \) the collision is completely inelastic. Now using this condition, together with Equation 2.13, the ‘balance’ of energy reads (assuming \( \tilde{V}_{A1} = 0 \)),

\[ \frac{1}{2} m_{B1} |\tilde{V}_{B1}|^2 = \frac{1}{2} m_{A1} |\tilde{V}_{A1}|^2 + \frac{1}{2} m_{B2} |\tilde{V}_{B2}|^2. \] (4.5)

Now following the same procedure as Section 2.5, this leads to a new expression for Equation 2.18

\[
\begin{align*}
\tilde{u}_{A2} &= \left(1 + \sqrt{1 - (1 - \varepsilon)(M + 1)}\right)\frac{\lambda}{M + 1} \left( u_{B1,\perp} \cos \gamma + u_{B1,\parallel} \sin \gamma \right), \\
\tilde{u}_{B2} &= \frac{1 - \lambda - M}{M + 1} \left( u_{B1,\perp} \cos \gamma + u_{B1,\parallel} \sin \gamma \right) + \left( -u_{B1,\perp} \sin \gamma + u_{B1,\parallel} \cos \gamma \right),
\end{align*}
\] (4.6)

where \( M = \frac{m_{A2}}{m_{B2}} \) is the mass ratio of the droplets after the collision.

Table 4.2 Comparison of the theoretical and experimental velocities of the DOD and CIJ droplets after the collision, using the elasticity factor and energy loss factor. The ratios are the experimental values divided by the theoretical values.

<table>
<thead>
<tr>
<th>I [-]</th>
<th>Theo. CIJ [m/s]</th>
<th>Exp. CIJ [m/s]</th>
<th>Ratio CIJ</th>
<th>Theo. DOD [m/s]</th>
<th>Exp. DOD [m/s]</th>
<th>Ratio DOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serie 1</td>
<td>0.74</td>
<td>8.79</td>
<td>8.9 ± 1.9</td>
<td>1.01</td>
<td>9.67</td>
<td>6.5 ± 1.1</td>
</tr>
<tr>
<td></td>
<td>0.67</td>
<td>8.75</td>
<td>9.7 ± 1.2</td>
<td>1.10</td>
<td>10.84</td>
<td>5.9 ± 3.1</td>
</tr>
<tr>
<td></td>
<td>0.61</td>
<td>8.66</td>
<td>9.7 ± 0.5</td>
<td>1.11</td>
<td>12.00</td>
<td>7.8 ± 0.5</td>
</tr>
<tr>
<td>Serie 2</td>
<td>0.79</td>
<td>8.48</td>
<td>7.8 ± 1.7</td>
<td>0.88</td>
<td>8.57</td>
<td>2.4 ± 0.7</td>
</tr>
<tr>
<td></td>
<td>0.69</td>
<td>8.54</td>
<td>8.1 ± 2.0</td>
<td>0.95</td>
<td>10.13</td>
<td>6.7 ± 1.4</td>
</tr>
<tr>
<td></td>
<td>0.64</td>
<td>8.56</td>
<td>7.7 ± 1.3</td>
<td>0.90</td>
<td>10.67</td>
<td>4.1 ± 0.2</td>
</tr>
<tr>
<td>Serie 3</td>
<td>0.75</td>
<td>11.16</td>
<td>9.7 ± 1.6</td>
<td>0.87</td>
<td>12.36</td>
<td>4.8 ± 0.6</td>
</tr>
<tr>
<td></td>
<td>0.71</td>
<td>11.10</td>
<td>9.1 ± 0.9</td>
<td>0.82</td>
<td>13.51</td>
<td>7.5 ± 0.7</td>
</tr>
<tr>
<td></td>
<td>0.68</td>
<td>11.15</td>
<td>9.1 ± 0.8</td>
<td>0.82</td>
<td>13.91</td>
<td>9.0 ± 0.8</td>
</tr>
<tr>
<td></td>
<td>0.66</td>
<td>11.13</td>
<td>9.8 ± 0.1</td>
<td>0.88</td>
<td>14.31</td>
<td>7.6 ± 0.3</td>
</tr>
</tbody>
</table>
Equation 2.30 is still valid, so using this equation, the velocities, according to the kinetic energy loss, compared to the velocities found from the pictures are given in Table 4.2. From the table can be seen that the theoretical velocities are more close to the experimental velocities, than found in Table E1 - Table E3, which means that the ratios are closer to 1, especially the velocities for the CIJ droplets. Also, the ratios become smaller (a bigger difference between the velocities) when the initial velocity of the CIJ droplets increases.

**Stretching kinetic energy**

In the collisions with the stretching separation result, only a small part of both droplets is involved in the collision (because of the higher impact parameter), the remaining volumes tend to move in the direction of their initial trajectory. This stretching kinetic energy consists out of two parts, the kinetic energy from the region of interaction and the remaining part of the total kinetic energy [10]. First, the energy in the interaction region. The width of this area (see also Figure 4.8) is the sum of the radii of both droplets minus the impact parameter,

\[
h = \frac{1}{2}(d_{CIJ} + d_{DOD})(1 - I) = (R_{CIJ} + R_{DOD})(1 - I). \tag{4.7}
\]

The volumes of this interacting region are given by

\[
V_{Ai} = \phi_A V_A, \tag{4.8}
\]

\[
V_{Bi} = \phi_B V_B, \tag{4.9}
\]

where

\[
\phi_A = \begin{cases} 
1 - \frac{1}{4}(2 - \tau)^2(1 + \tau) & h > \frac{1}{2}d_{CIJ} \\
\frac{\tau^2}{4}(3 - \tau) & h < \frac{1}{2}d_{CIJ}
\end{cases}
\tag{4.10}
\]

\[
\phi_B = \begin{cases} 
1 - 2(1 - \tau)^2\left(\frac{1}{2} + \tau\right) & h > \frac{1}{2}d_{DOD} \\
2\tau^2\left(\frac{3}{2} - \tau\right) & h < \frac{1}{2}d_{DOD}
\end{cases}
\tag{4.11}
\]
where $\tau \equiv \frac{3}{2} (1 - I)$ for droplets with diameter ratio $\Delta = \frac{d_{DOD}}{d_{CJ}} = 0.5$.

This leads to the total stretch energy [10]

$$E_{ss} = \frac{1}{2} \rho_A \left[ (V_A - V_{AI1}) \left| \vec{v}_{AI1} \right|^2 \right] + \frac{1}{2} \rho_B \left[ (V_B - V_{AI1}) \left| \vec{v}_{AI1} \right|^2 \right] + \frac{1}{2} \rho_A \left[ (V_{AI1} - (\vec{v}_{AI1} \cos \alpha) \right]^2 + \frac{1}{2} \rho_A \left[ (V_{AI1} - (\vec{v}_{AI1} \sin \alpha) \right]^2$$

(4.12)

where $\sin \alpha = I$ and the first two terms represent the kinetic energy of the region outside the region of interaction and the third and forth term represent the kinetic energy of the interacting region.

**Surface tension energy**

The surface tension energy at the region of interaction acts against the stretching energy, because at the moment the stretching energy is bigger than the surface tension energy, the two droplets separate. The surface tension energy is defined as

$$E_{surf} = \sigma_A \pi R_{AI2}^2 + \sigma_B \pi R_{BI2}^2.$$  

(4.13)

**Rotation energy**

When two droplets collide, the produced droplet will rotate with an angular momentum $\Omega$ about its center of gravity [28]. To separate again into two droplets, the angular momentum should reach a critical value. Therefore, the rotation energy associated with this angular momentum, is given as [28]

$$E_{rot} = \frac{5 \pi \rho_m u_{rel}^2 b^2 r_A^2 r_B^6}{3 R_0^{11}},$$

(4.14)

where $b$ is the impact parameter, $R_0$ is the radius of the coagulated drop pair and $\rho_m$ the density of the combined droplets. After the collision, the droplets could also rotate themselves.

For an approximation of the rotation energy, the following is assumed: if the two droplets collide and there is no rotation before the collision, the droplets can rotate with maximum the velocity of the droplet they collide with; so the CIJ droplet can rotate with maximum the initial velocity of the DOD droplet and vice versa, so

$$E_{rot} \leq \frac{1}{2} \frac{I \omega^2}{2} = \frac{1}{2} \frac{v_{d1}^2}{r_d^2} m_d r_d^2 = \frac{1}{5} \frac{m_d v_{d1}^2}{r_d^2},$$

(4.15)

where $I$ is the moment of inertia for a solid sphere [14].

Approximations of the energies after the collision are shown in Table 4.3. From this table can be seen that still a part of the energy is unaccounted. Therefore, we zoom onto the collision.
Table 4.3 Average energies for kinetic energy before the collision and the stretching, rotation and surface tension energy after the collision of a tri-ethylene droplet and water droplet, with parameters of serie 2. All energies are valid for the stretching separation regime. Energies are calculated using Equations 4.12 - 4.15. The kinetic energy before the collision minus all energies after the collisions is the rest energy.

<table>
<thead>
<tr>
<th>$E_{\text{kin,1}}$ [J]</th>
<th>$E_{\text{str}}$ [J]</th>
<th>$E_{\text{rot}}$ [J]</th>
<th>$E_{\text{surf}}$ [J]</th>
<th>Rest [J]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.77 ·10^{-8}</td>
<td>2.35 ·10^{-8}</td>
<td>0.16 ·10^{-8}</td>
<td>0.05 ·10^{-8}</td>
<td>0.22 ·10^{-8}</td>
</tr>
</tbody>
</table>

4.2.3 Zooming onto the collision

For all data analysis of the velocities, volumes and trajectories, the minimum zoom of the cameras is used. But, as already mentioned in Section 3.3, the lenses give the possibility to zoom. Zooming onto the collision, the mass transfer can be observed very clearly, but, unfortunately, the amount of mass transfer cannot be observed, because on all images the shadows of the droplets are shown, which are black spots and from these black spots it is not possible to see what is going on in there. Therefore, observing the collision using a color CCD-camera and using a dye in one of the droplets (which does not affect the properties of the liquid), could bring a solution. Pictures of a zoomed in collision are shown in Figure 4.9. In the first picture, just after the collision, the two droplets are still connected; the mass transfer from the DOD droplet to the CIJ droplet is visible; in the second picture the two droplets separated again, which means the stretching energy is bigger than the surface energy. In the third picture, which is also just after separation but from another collision, a satellite droplet is created and the DOD droplet is vibrating to return to its original spherical shape. In the last picture, the satellite droplet is completely created, and the DOD droplet is still vibrating. From all pictures can be seen that the droplets change in shape after the collision and that they vibrate to their initial spherical shape. The vibration of the droplets has big influence on both droplets after the collision, which means the vibration energy is important as well. This means that, most probable, the unaccounted ‘rest’ energy, as found in Table 4.3, is an approximation for the vibration energy. Because these vibrations also occur at bouncing, the energies are also calculated for these results. These average energies for the stretching separation and bouncing regimes are shown in Table 4.4. From this table can be seen that the kinetic energy before the collision is lost for the major part by the ‘calculated’ rotation energy and the vibration energy. This can be seen from the fact that the stretching energy contains the remaining part of the kinetic energy after the collision, as can be seen from Equation 4.12.

Table 4.4 Average energies for kinetic energy before the collision and the stretching, rotation and surface tension energy after the collision of a tri-ethylene droplet and water droplet, with parameters of serie 2. All energies are valid for the stretching separation and bouncing regime. Energies are calculated using Equations 4.12 - 4.15. The kinetic energy before the collision minus all energies after the collisions is the rest energy.

<table>
<thead>
<tr>
<th>$E_{\text{kin,1}}$ [J]</th>
<th>$E_{\text{str}}$ [J]</th>
<th>$E_{\text{rot}}$ [J]</th>
<th>$E_{\text{surf}}$ [J]</th>
<th>Rest [J]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.77 ·10^{-8}</td>
<td>2.46 ·10^{-8}</td>
<td>0.16 ·10^{-8}</td>
<td>0.05 ·10^{-8}</td>
<td>0.10 ·10^{-8}</td>
</tr>
</tbody>
</table>

As mentioned in the upper section, the total mass transfer cannot be determined from the images. Another possibility is collecting the droplets after the collision and measure the viscosity, surface tension or density. For measuring these properties, the available techniques need a relative large quantity (number) of liquid/droplets (e.g. for measuring the surface tension or viscosity 20 mL (which is 32 ·10^6 droplets) is necessary), which is impossible to collect from stable collisions. The only possibility was measuring the density (‘only’ 2 mL (or 3.2 ·10^6 droplets) is needed). The apparatus should measure the difference in density between a collision with the coalescence outcome and with a bouncing result. Calculations of the densities of the collected
mixtures after collisions give $\rho_{\text{coalescence}} = 1.12719 \text{ g/cm}^3$ and

$\rho_{\text{bounce}} = 1.12712 \text{ g/cm}^3$. This means, the difference should be measured in, at least, five digits (10 ppm). Such an apparatus was not available during this project, so this has not been measured. Not only the accuracy of this apparatus is important for the measurement, but also the rest of the set-up should be this accurate, e.g. no contamination from dust particles in the air during the experiment, so even when this apparatus is available, the measurement is really difficult.

4.2.4 Total energy loss

As can be seen from the previous paragraphs, the droplets loose kinetic energy in different processes. Comparing the velocities of the droplets after the collision from the experiments with the theory, there is a kinetic energy loss caused by the stretching energy, rotation energy, surface tension energy, vibration energy, but it is also possible there is a heat transfer in the collision. Only approximations of the energies can be made, due to the fact that the rotation cannot be observed from the shadow, and the major part of the ‘rest’ energy is assigned to the vibration energy. Figure 4.3 already showed that a boundary layer is present on the CIJ droplet stream. This boundary layer deflects the DOD droplet, which also leads to a variation in velocity. Also the transversal reacting force, as explained in paragraph 2.7.2 has small influence on the deflected CIJ droplet.

In the coalescence regime also a kinetic energy loss occurs, but here, the main cause is the vibration energy.
4.3 Deflections

One of the aims of the project was to find a range where the CIJ droplets are deflected at least 2° from the droplet stream, such that it is possible to collect them after the collision for recycling. Therefore, the trajectory of the droplets is followed in the stream and the angle of deflection is calculated. The range is determined using the stretching separation, bouncing and coalescence outcomes of serie 3, at the boundary of the predicted line from Figure 4.6. In Figure 4.10, the CIJ droplet is shown at a position of 7 mm under the collision point.

From Figure 4.10 can be learned that for the different impact parameters for stretching separation and bouncing, as well as for the parameters for coalescence, close to the predicted separations curve, the angle of deflection is 2.8°. This angle is determined by determination of the ‘line of movement’, i.e. the trajectory of the droplet stream from the point of collision, and the position of the affected droplet. The angle between this line of movement and the affected droplet is the angle of deflection. This principle is also shown in Figure 4.10a.

Figure 4.10e and Figure 4.10f represents the coalescence results. The purpose of the project was to deflect the droplets from the droplet stream with a minimal deflection angle of 2°, where both droplets can be collected after the collision for recycling. Therefore, coalescence is not a useful result, because both droplets cannot be recycled, so also the impact parameters, related to these results are not useful. From Figure 4.10d can be seen that the bouncing result does not have a deflection angle of 2°, but less. Therefore, the requirement can not be satisfied.

Now, it can be concluded, using Figure 4.6 and Figure 4.10, the range of impact parameters which deflects a CIJ droplet out of the stream at least 2° for We = 308, is $0.58 \leq I \leq 0.83$. For We = 160 the collisions gave the same results, but here the range for impact parameter is $0.64 \leq I \leq 0.80$. This also means that the preferred result of the collision is stretching separation. The deflection angles after the collisions with bouncing results are also acceptable, but these angles are smaller. Comparing this range with the range found in Section 2.5, it shows that both ranges agree, so the experiments agree with the theoretical values. The ranges found in the theoretical calculations are larger; the reason for this is that in the calculations the collisions between the droplets are assumed to be completely elastic, while in the experiments this is not the case. Also, all other effects, like vibration and rotation are neglected in the calculations, but are present in the experiments. In appendix F the complete trajectory of the affected CIJ droplet and the DOD droplet are shown.
Figure 4.10 Deflected CIJ droplet from stream for different impact parameters, at 7 mm under collision point; $v_{CIJ} = 11 \text{ m/s}$, $v_{DOD} = 1.6 \text{ m/s}$. a) definition of the line of movement, b) $I = 0.66$, c) $I = 0.75$, d) $I = 0.79$, e) $I = 0.53$, f) $I = 0.51$. $We = 308$. The measured angles of deflection are given next to the pictures.
5 Conclusion and Recommendations

The experimental results of collisions between two droplets colliding at different impact parameters and different Weber numbers, agree with the theoretical results; the curves found by others [8], to predict the results of the collisions between two droplets of the same liquid, are also valid for collisions between droplets of different liquids, and even the graph can be extrapolated to higher Weber numbers. The regimes of the results for these collisions are bouncing, stretching separation and coalescence. For the use of the collisions as deflection method, the range where the CIJ droplets are deflected more than 2° and where both droplets can be collected for recycling, for this case, is $0.64 \leq I \leq 0.80$ for a Weber number of 160 and increases to $0.58 \leq I \leq 0.83$ for Weber numbers larger than 300. These experimental determined ranges are in good agreement with the theoretical, calculated ranges, but these calculated ranges are larger: $0.5 \leq I \leq 0.97$. This can be explained by the fact the calculations assume a completely elastic collision, and neglect the vibrations and rotations. Also, if the requirement of the deflection angle is reduced to a smaller angle, both experimentally found ranges are increased to $0.58 \leq I \leq 1$.

From the experiments can be learned that the kinetic energy is not conserved during the collisions, but a part of the kinetic energy is converted into other energies: during the stretching separation, mass transfers from the DOD droplet into the CIJ droplet and, frequently, satellite droplets are created. The mass transfer during these collisions is always from the smaller DOD droplet to the larger CIJ droplet, due to the fact the pressure in the small droplet is higher than the pressure in the CIJ droplet. The droplets probably start rotating after the collision. Another factor which is important for the energy loss is the tendency of the droplets to return to their initial spherical shape after the collision. After the collision the droplets start vibrating. From the calculations using the velocities of the droplets after the collision can be seen that the major part of the kinetic energy loss is can be explained by conversion into rotation and vibration energy.

The DOD droplets are deflected by the boundary layer surrounding the CIJ droplet stream. This effect of the boundary layer has been observed experimentally. 3D numerical simulations of the geometry of the droplet stream, used in these experiments, show that this boundary layer can be described with the equation for the boundary layer on a continuous flat surface. When a droplet is translated out of the droplet stream, the drag force acting on this droplet can be separated into two components: one in the axial direction and one in the transversal direction: the transversal reacting force is acting onto this droplet to force it back into the stream; this transversal reacting force is much smaller than the drag force acting on the droplet. For a droplet stream where the distance between the droplets is 2 droplet diameters, and the droplet is translated a distance equal to its diameter out of the stream, this droplet can be interpreted as a free droplet translating in air. This ejection of the droplet from the stream has also influence on the stability of the droplet stream: the next droplet in the stream slows down, and the distance between the droplets decreases. Therefore, the distance between the collision point and the substrate should be small, otherwise the droplets in the stream coalesce. This instability of the droplets in the stream also occurs naturally; due to the difference in drag force for the different droplets in the stream, the velocities for the droplets are changing and the distances between the droplets in the stream changes. The collisions should performed as close to the nozzle of the CIJ as possible, to control the impact parameter of the collision.
In principle, collisions with other droplets as deflection method are usable in a 20 kHz printing process, but not as a continuous process, unless the stability of the droplet stream is increased. It is showed that it is possible to deflect one single droplet from the continuous droplet stream; something that was not possible before. In these experiments, during 15 minutes, the deviation in vertical droplet position is approximately 1 droplet diameter. The use of a feedback loop can increase the stability of the CIJ droplet stream. Changing the amplitude of the piezo translator changes the distance between the droplets. Using a feedback loop, which controls the amplitude, gives the possibility to adjust the amplitude when a deviation in droplet position is observed. This principle can increase the stability of the droplet stream, which gives the opportunity to print continuous.

Another possibility is getting the CIJ droplet stream more stable over longer time by changing the pump. Now, the pulsations of the pump are still visible in the droplet stream, even with the preferred pressure on the damper. Using another pump which does not give these pulsations could solve this instability.

For further investigation of the mass transfer between the droplets during the collision, the use of a dye, which does not affect the properties of the liquid, and a color CCD camera is recommended. Also measuring the density of the mixture after the collisions is an option; however this method requires a high accuracy (10 ppm).

Since the deflection method is successful for a highly viscous liquid, which is soluble in water, my expectation is that the deflections are also successful for more viscous liquids, and that the range of impact parameters for stretching separation, as well as the range for bouncing, will increase and the requirement of the minimum deflection angle of 2° is satisfied.

The requirement of a deflection of 2°, with collecting both droplets can be satisfied, but for a print system where the collecting requirement is released and only the 2° deflection angle is required, the range of impact parameters increases, because the droplets after collisions with a coalescence result also have a deflection angle of 2°. Therefore it is easier to deflect the ‘target droplet’ from the droplet stream, because the range of ‘successful’ collisions is larger. This, combined with the feedback loop to control the amplitude, increases the possibility of success of the deflections and, with further research and experiments on the deflection of more droplets, can lead to a successful continuous printing deflection method.

An alternative method for deflecting droplets at higher frequency could be the use of another CIJ print head instead of the DOD print head, but printing at lower frequency. The problem with this method is that the droplets in the droplet stream cannot be deflected on demand. In order to make this deflection method industrial applicable, increasing the frequency of the DOD droplets is necessary. But, in this project it was experimentally found that the DOD droplets are more unstable if the frequency increases, so further research is needed. Using more DOD print heads vertically placed under each other, or in a kind of ‘ring’ around the CIJ droplet stream, are also ways to increase the ‘deflection frequency’. Using these methods, but also using a CIJ print head instead of the DOD print head, more droplets are deflected from the droplet stream. The influence of the deflected droplets on the droplet stream, as well as the behaviour of the droplets in the droplet stream is unknown and should be investigated. My expectation is that the droplet stream becomes more unstable and the substrate should be placed a small distance under the deflection point, otherwise too many droplets in the droplet stream will coalesce with each other. But with some changes in the experimental set-up, this ‘problem’ can be solved.
Because the collisions of the droplets are successful, and especially the range of coalescence is large (0 ≤ I ≤ 0.5), the collisions can be used for multi-material printing. Using a small droplet, maybe much smaller than the used droplets is this project, which is shot on a larger droplet and if the collision between the droplets starts a reaction, this reaction product is deposited onto the substrate as well. This gives the opportunity to print with different materials. Another application can be in-flight coating of droplets: droplets in the continuous stream which make a collision with smaller droplets and the results is stretching separation, the ‘coating’ which is present can flow from the smaller droplet to the larger droplet. Now, if the coating and target droplet are chosen in a way that the coating will flow to the boundary of this target droplet, the larger droplet can be coated. Both future applications are shown in Figure 5.1.

![Multi-material printing and coating](image)

**Figure 5.1** Recommendations of future applications of the use of two print heads, a) multi-material printing and b) coating of droplets.
6 References


[17] S. Leichtberg et al., *A study of unsteady forces at low Reynolds number: a strong interaction theory for the coaxial settling of three or more spheres*, Phil. Trans. R. Soc. Lond. A, 1976, **282**(585)


Acknowledgements

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Then, Jurjen, Ruud, Maurice, Raymond and Erwin, thanks for the support and for the nice atmosphere and discussions in the office. And thanks to all others in the IMC and Rapid Manufacturing groups of TNO for all input and help.
And, finally, I am very grateful to my girlfriend, Annelies, and my parents, for supporting me in many different ways (not only) during this project and the writing of this report.
A Transformation velocity vectors

Transformation of a velocity vector has the advantage to separate this vector in a normal and a tangential component. The velocity vector is given by

\[
\begin{align*}
\vec{u}_{Bl} &= u_{Bl,x} \cdot \vec{e}_x + u_{Bl,y} \cdot \vec{e}_y = u_{Bl,n} \cdot \vec{e}_n + u_{Bl,t} \cdot \vec{e}_t \\
&= u_{Bl,n} \cdot \vec{e}_n + u_{Bl,t} \cdot \vec{e}_t + 2\pi \gamma \pi \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma 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\gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma \gy
B Drag force relations and constants

The relations of the drag force $C_D$ and the Reynolds number, as given in Clift et al. [16]:

Table B 1 Relations drag force and Reynolds number for rigid spheres, $w = \log_{10} \text{Re}$.

<table>
<thead>
<tr>
<th>Range Reynolds number $Re$</th>
<th>Drag force $C_D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Re &lt; 0.01$</td>
<td>$C_D = 3/16 + 24/Re$</td>
</tr>
<tr>
<td>$0.01 &lt; Re \leq 20$</td>
<td>$C_D = \frac{24}{Re} \left[ 1 + 0.1315 \text{Re}^{(0.82-0.05w)} \right]$</td>
</tr>
<tr>
<td>$20 \leq Re \leq 260$</td>
<td>$C_D = \frac{24}{Re} \left[ 1 + 0.1935 \text{Re}^{0.6305} \right]$</td>
</tr>
<tr>
<td>$260 \leq Re \leq 1500$</td>
<td>$\log_{10} C_D = 1.6435 - 1.1242w + 0.1558w^2$</td>
</tr>
<tr>
<td>$1.5 \cdot 10^3 \leq Re \leq 1.2 \cdot 10^4$</td>
<td>$\log_{10} C_D = -2.4571 + 2.5558w - 0.9295w^2 + 0.1049w^3$</td>
</tr>
<tr>
<td>$1.2 \cdot 10^4 \leq Re \leq 4.4 \cdot 10^4$</td>
<td>$\log_{10} C_D = -1.9181 + 0.6370w - 0.0636w^2$</td>
</tr>
<tr>
<td>$4.4 \cdot 10^4 \leq Re \leq 3.38 \cdot 10^5$</td>
<td>$\log_{10} C_D = -4.3390 + 1.5809w - 0.1546w^2$</td>
</tr>
<tr>
<td>$3.38 \cdot 10^5 \leq Re \leq 4 \cdot 10^5$</td>
<td>$C_D = 29.78 - 5.3w$</td>
</tr>
<tr>
<td>$4 \cdot 10^5 &lt; Re \leq 10^6$</td>
<td>$C_D = 0.1w - 0.49$</td>
</tr>
<tr>
<td>$10^6 &lt; Re$</td>
<td>$C_D = 0.19 - 8 \cdot 10^{-4}/\text{Re}$</td>
</tr>
</tbody>
</table>

B.1 Procedure simulation of influence gravity

The procedure of the simulation of the influence of gravity and air drag at the trajectories of a water droplet, as shown in Figure 2.14, is described here.

The acceleration of the droplet $a_x$ and $a_y$ are changing constantly as the velocity of the droplet changes; but over a short interval the acceleration can be considered as constant:

$$a = \frac{\Delta v}{\Delta t} \rightarrow \Delta v_x = a_x \Delta t \rightarrow v_x + \Delta v_x = v_x + a_x \Delta t$$

$$a = \frac{\Delta v}{\Delta t} \rightarrow \Delta v_y = a_y \Delta t \rightarrow v_y + \Delta v_y = v_y + a_y \Delta t$$

which gives for the displacement

$$\Delta x = \left(v_x + \frac{\Delta v_x}{2}\right)\Delta t = v_x \Delta t + \frac{1}{2} a_x \Delta t^2 \Rightarrow x + \Delta x = x + v_x \Delta t + \frac{1}{2} a_x \Delta t^2$$

$$\Delta y = \left(v_y + \frac{\Delta v_y}{2}\right)\Delta t = v_y \Delta t + \frac{1}{2} a_y \Delta t^2 \Rightarrow y + \Delta y = y + v_y \Delta t + \frac{1}{2} a_y \Delta t^2$$

Using Equation 2.46b for the mass of the droplet gives, using Equation 2.42 and Equation 2.45, for the acceleration terms in Equation B 2...
\[ a_x = -\frac{3 \rho_{\text{air}}}{8 \rho_D} \frac{C_D}{r_D} v_x \sqrt{v_x^2 + v_y^2} \]

\[ a_y = -g - \frac{3 \rho_{\text{air}}}{8 \rho_D} \frac{C_D}{r_D} v_y \sqrt{v_x^2 + v_y^2} . \]

(B 4)

## B.2 Constants

Some typical values for the density and viscosity:

\( \mu_{\text{air}} = 18.1 \cdot 10^{-6} \text{ Pa s (at 20°C, 1 atmosphere)} \)

\( \mu_{\text{water}} = 1000 \cdot 10^{-6} \text{ Pa s (at 20°C, 1 atmosphere)} \)

\( \mu_{\text{tri-ethylene-glycol}} = 38.8 \cdot 10^{-3} \text{ Pa s} \)

\( \rho_{\text{air}} = 1.293 \text{ kg m}^{-3} \)

\( \rho_{\text{water}} = 0.998 \cdot 10^{-3} \text{ kg m}^{-3} \)

\( \rho_{\text{tri-ethylene-glycol}} = 1.124 \cdot 10^{-3} \text{ kg m}^{-3} \)
C Simulation 2D droplets

The results from the velocity field from the simulations of 2D droplets in a stream, moving in air with a velocity of 8 m/s, are given in the next figures. The diameter of the droplets is 100 µm, the gap distance between the droplets is 300 µm. In each figure the drag force acting on each droplet is given, as well as the transversal reacting force. In each graph, blue represents 8 m/s, red 0 m/s.

Figure C 1 Droplet is translated 0 µm out of stream. The numerical uncertainty is $7 \cdot 10^{-6}$ N/m, as can be seen from the graph of the transversal reacting force, because this force per length unit, should be 0 N/m for a droplet stream where none of the droplets is translated.
Figure C 2  Droplet is translated 10 µm out of stream.

Figure C 3  Droplet is translated 20 µm out of stream.
Figure C.4   Droplet is translated 30 µm out of stream.

Figure C.5   Droplet is translated 40 µm out of stream.
Figure C 6  Droplet is translated 50 µm out of stream.

Figure C 7  Droplet is translated 60 µm out of stream.
Figure C 8  Droplet is translated 70 µm out of stream.

Figure C 9  Droplet is translated 80 µm out of stream.
Figure C 10  Droplet is translated 90 µm out of stream.

Figure C 11  Droplet is translated 100 µm out of stream.
Figure C 12  Droplet is translated 110 μm out of stream.

Figure C 13  Droplet is translated 120 μm out of stream.
The simulations of the boundary layer on a continuous flat plate, cylinder and droplet stream relations for the thickness of the boundary layer as function of the displacement distance were found from Figure 2.26, using the slope of this graph. The creation of the boundary layers as function of the displacement distance is shown in Figure C 14.

Figure C 14 Boundary layer thickness around a moving cylinder, with \( v = 8 \text{ m/s} \) and \( r_{\text{cyl}} = 50 \mu\text{m} \). The result of the simulation, the best fit through the simulation (Equation 2.58), the boundary layer around the continuous flat plate (Equation 2.54) and the layer around the droplet stream are also plotted.
D Experimental set-up

First, the TTL pulse is described, than some pictures of the experimental set-up are shown and finally the importance of the resolution is described.

The auxiliary output signal (AUX) of the function generator creates a TTL signal, with the same frequency of the sine wave. This TTL-signal is a square wave, with a maximum of 5V and a minimum of 0V. The TTL signal is given in Figure D 1. The SYNC output of the AWG is the same as the AUX from the function generator: when the arbitrary wave starts, a TTL pulse is send as a trigger pulse to the camera.

![TTL signal compared with a normal sine wave.](image)

Pictures of the set-up are given in the next figures. The explanation of all parts is given in Section 3.2.

![The experimental set-up.](image)
Figure D 3  Positioning of the two print heads: the DOD print head is placed under 60° in respect to the CIJ droplet stream, at a distance of 2.3 mm.

Figure D 4  Electrical components in the experimental set-up.
The resolution of the pictures is really important, because all the information from the experiments is gained from these pictures. To show the importance that the distance from the camera to the droplet stream is constant, pictures of the droplet stream with different distance variations are shown in Figure D 5. The distance which is used in the experiments is 5.1 cm, the depth of field from the set-up is, using the minimum zoom, 1.35 mm.

![Droplets in focus](image1.png) ![Droplets not in focus](image2.png) ![Droplets completely not in focus](image3.png)

Figure D 5 Variation in distance between droplet stream and camera. From the droplets which are not in focus, no information can be gained, because the diameter of the droplets is unknown.
E  Velocities droplets after collision: theoretical and experimental

From the pictures of the collisions, the velocity of the DOD and CIJ droplets can be determined. These velocities can also be determined theoretically, using Section 2.5. From the series 1-3, the velocities of the droplets after the collision are given in the next tables. For the results of stretching separation and coalescence, also the elasticity number $\lambda$ is given; for a completely inelastic collision (coalescence) $\lambda = 1$, for a completely elastic collision (bouncing) $\lambda = 0$. Also the ratio between the experimental and theoretical velocity is given.

Table E 1  Serie 1: Comparison between theoretical and experimental velocities of droplets after the collision.

<table>
<thead>
<tr>
<th>I [-]</th>
<th>$\lambda$ [-]</th>
<th>Theo. CIJ [m/s]</th>
<th>Exp. CIJ [m/s]</th>
<th>Ratio CIJ [-]</th>
<th>Theo. DOD [m/s]</th>
<th>Exp. DOD [m/s]</th>
<th>Ratio DOD [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.93</td>
<td>0</td>
<td>8.48</td>
<td>8.0 ± 0.7</td>
<td>0.94</td>
<td>4.46</td>
<td>2.3 ± 0.2</td>
<td>0.52</td>
</tr>
<tr>
<td>0.88</td>
<td>0</td>
<td>8.37</td>
<td>8.6 ± 0.5</td>
<td>1.02</td>
<td>6.11</td>
<td>1.7 ± 0.1</td>
<td>0.28</td>
</tr>
<tr>
<td>0.82</td>
<td>0</td>
<td>8.23</td>
<td>9.4 ± 0.5</td>
<td>1.14</td>
<td>7.67</td>
<td>5.0 ± 1.3</td>
<td>0.65</td>
</tr>
<tr>
<td>0.74</td>
<td>0.37</td>
<td>11.16</td>
<td>8.9 ± 1.9</td>
<td>0.79</td>
<td>12.39</td>
<td>6.5 ± 1.1</td>
<td>0.52</td>
</tr>
<tr>
<td>0.67</td>
<td>0.37</td>
<td>11.07</td>
<td>9.7 ± 1.2</td>
<td>0.87</td>
<td>13.85</td>
<td>5.9 ± 3.1</td>
<td>0.43</td>
</tr>
<tr>
<td>0.61</td>
<td>0.55</td>
<td>10.97</td>
<td>9.7 ± 0.5</td>
<td>0.88</td>
<td>15.04</td>
<td>7.8 ± 0.5</td>
<td>0.52</td>
</tr>
</tbody>
</table>

Table E 2  Serie 2: Comparison between theoretical and experimental velocities of droplets after the collision.

<table>
<thead>
<tr>
<th>I [-]</th>
<th>$\lambda$ [-]</th>
<th>Theo. CIJ [m/s]</th>
<th>Exp. CIJ [m/s]</th>
<th>Ratio CIJ [-]</th>
<th>Theo. DOD [m/s]</th>
<th>Exp. DOD [m/s]</th>
<th>Ratio DOD [-]</th>
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</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0</td>
<td>8.4</td>
<td>8.4 ± 14</td>
<td>1.00</td>
<td>1.50</td>
<td>3.2 ± 0.6</td>
<td>2.15</td>
</tr>
<tr>
<td>0.95</td>
<td>0</td>
<td>8.34</td>
<td>8.3 ± 1.4</td>
<td>1.00</td>
<td>3.32</td>
<td>5.4 ± 3.1</td>
<td>1.63</td>
</tr>
<tr>
<td>0.89</td>
<td>0</td>
<td>8.22</td>
<td>8.0 ± 1.5</td>
<td>0.97</td>
<td>5.47</td>
<td>2.7 ± 0.7</td>
<td>0.49</td>
</tr>
<tr>
<td>0.79</td>
<td>0.63</td>
<td>11.16</td>
<td>7.8 ± 1.7</td>
<td>0.70</td>
<td>11.14</td>
<td>2.4 ± 0.7</td>
<td>0.23</td>
</tr>
<tr>
<td>0.73</td>
<td>0</td>
<td>7.87</td>
<td>6.1 ± 0.7</td>
<td>0.78</td>
<td>8.98</td>
<td>4.9 ± 0.3</td>
<td>0.55</td>
</tr>
<tr>
<td>0.69</td>
<td>0.55</td>
<td>11.06</td>
<td>8.1 ± 2.0</td>
<td>0.74</td>
<td>13.41</td>
<td>6.7 ± 1.4</td>
<td>0.50</td>
</tr>
<tr>
<td>0.64</td>
<td>0.25</td>
<td>11.00</td>
<td>7.7 ± 1.3</td>
<td>0.70</td>
<td>14.18</td>
<td>4.1 ± 0.2</td>
<td>0.29</td>
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</table>

Table E 3  Serie 3: Comparison between theoretical and experimental velocities of droplets after the collision.

<table>
<thead>
<tr>
<th>I [-]</th>
<th>$\lambda$ [-]</th>
<th>Theo. CIJ [m/s]</th>
<th>Exp. CIJ [m/s]</th>
<th>Ratio CIJ [-]</th>
<th>Theo. DOD [m/s]</th>
<th>Exp. DOD [m/s]</th>
<th>Ratio DOD [-]</th>
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<tbody>
<tr>
<td>0.94</td>
<td>0</td>
<td>10.87</td>
<td>10.7 ± 0.1</td>
<td>0.99</td>
<td>5.25</td>
<td>2.6 ± 0.3</td>
<td>0.50</td>
</tr>
<tr>
<td>0.90</td>
<td>0</td>
<td>10.75</td>
<td>10.8 ± 0.1</td>
<td>1.00</td>
<td>7.10</td>
<td>2.7 ± 0.1</td>
<td>0.37</td>
</tr>
<tr>
<td>0.84</td>
<td>0</td>
<td>10.57</td>
<td>9.8 ± 1.2</td>
<td>0.93</td>
<td>9.20</td>
<td>4.4 ± 0.9</td>
<td>0.48</td>
</tr>
<tr>
<td>0.83</td>
<td>0</td>
<td>10.55</td>
<td>10.6 ± 0.1</td>
<td>1.01</td>
<td>9.53</td>
<td>2.9 ± 0.6</td>
<td>0.31</td>
</tr>
<tr>
<td>0.79</td>
<td>0</td>
<td>10.43</td>
<td>9.7 ± 1.3</td>
<td>0.93</td>
<td>10.65</td>
<td>4.8 ± 1.0</td>
<td>0.45</td>
</tr>
<tr>
<td>0.75</td>
<td>0.48</td>
<td>11.40</td>
<td>9.7 ± 1.6</td>
<td>0.85</td>
<td>11.96</td>
<td>4.8 ± 0.6</td>
<td>0.40</td>
</tr>
<tr>
<td>0.71</td>
<td>0.63</td>
<td>11.33</td>
<td>9.1 ± 0.9</td>
<td>0.80</td>
<td>12.97</td>
<td>7.5 ± 0.7</td>
<td>0.58</td>
</tr>
<tr>
<td>0.68</td>
<td>0.48</td>
<td>11.34</td>
<td>9.1 ± 0.8</td>
<td>0.80</td>
<td>13.47</td>
<td>9.0 ± 0.8</td>
<td>0.67</td>
</tr>
<tr>
<td>0.66</td>
<td>0.48</td>
<td>11.31</td>
<td>9.8 ± 0.1</td>
<td>0.86</td>
<td>13.85</td>
<td>7.6 ± 0.3</td>
<td>0.55</td>
</tr>
</tbody>
</table>
Table E 4  Comparison between theoretical and experimental velocities of the collisions with the coalescence outcome regime; $\lambda = 0$.

<table>
<thead>
<tr>
<th>I [-]</th>
<th>Theoretical velocity [m/s]</th>
<th>Experimental velocity [m/s]</th>
<th>Ratio [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Serie 1</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.61</td>
<td>8.72</td>
<td>8.8 ± 0.2</td>
<td>1.01</td>
</tr>
<tr>
<td>0.48</td>
<td>8.62</td>
<td>8.8 ± 0.1</td>
<td>1.02</td>
</tr>
<tr>
<td>0.41</td>
<td>8.56</td>
<td>8.8 ± 0.1</td>
<td>1.03</td>
</tr>
<tr>
<td>0.39</td>
<td>8.54</td>
<td>9.0 ± 0.2</td>
<td>1.05</td>
</tr>
<tr>
<td>0.35</td>
<td>8.50</td>
<td>8.7 ± 0.1</td>
<td>1.02</td>
</tr>
<tr>
<td>0.33</td>
<td>8.49</td>
<td>7.6 ± 0.2</td>
<td>0.90</td>
</tr>
<tr>
<td>0.32</td>
<td>8.49</td>
<td>7.4 ± 0.7</td>
<td>0.87</td>
</tr>
<tr>
<td>0.23</td>
<td>8.39</td>
<td>8.9 ± 0.2</td>
<td>1.07</td>
</tr>
<tr>
<td>0.14</td>
<td>8.32</td>
<td>8.0 ± 0.2</td>
<td>0.96</td>
</tr>
<tr>
<td>0.07</td>
<td>8.26</td>
<td>8.1 ± 0.4</td>
<td>0.98</td>
</tr>
<tr>
<td>0.01</td>
<td>8.21</td>
<td>7.2 ± 0.2</td>
<td>0.88</td>
</tr>
<tr>
<td><strong>Serie 2</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.57</td>
<td>8.49</td>
<td>6.6 ± 0.1</td>
<td>0.78</td>
</tr>
<tr>
<td>0.49</td>
<td>8.42</td>
<td>7.1 ± 0.5</td>
<td>0.84</td>
</tr>
<tr>
<td>0.43</td>
<td>8.37</td>
<td>6.6 ± 0.2</td>
<td>0.79</td>
</tr>
<tr>
<td>0.38</td>
<td>8.32</td>
<td>6.6 ± 0.2</td>
<td>0.80</td>
</tr>
<tr>
<td>0.35</td>
<td>8.31</td>
<td>6.5 ± 0.1</td>
<td>0.78</td>
</tr>
<tr>
<td>0.28</td>
<td>8.25</td>
<td>6.8 ± 0.1</td>
<td>0.83</td>
</tr>
<tr>
<td>0.26</td>
<td>8.22</td>
<td>6.6 ± 0.1</td>
<td>0.80</td>
</tr>
<tr>
<td><strong>Serie 3</strong></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>0.53</td>
<td>11.07</td>
<td>10.2 ± 0.6</td>
<td>0.92</td>
</tr>
<tr>
<td>0.52</td>
<td>11.06</td>
<td>9.8 ± 0.2</td>
<td>0.89</td>
</tr>
<tr>
<td>0.51</td>
<td>11.05</td>
<td>9.6 ± 0.2</td>
<td>0.87</td>
</tr>
<tr>
<td>0.39</td>
<td>10.92</td>
<td>10.1 ± 0.1</td>
<td>0.92</td>
</tr>
<tr>
<td>0.35</td>
<td>10.87</td>
<td>10.5 ± 0.3</td>
<td>0.97</td>
</tr>
<tr>
<td>0.28</td>
<td>10.80</td>
<td>10.1 ± 0.6</td>
<td>0.93</td>
</tr>
<tr>
<td>0.27</td>
<td>10.79</td>
<td>9.2 ± 0.1</td>
<td>0.86</td>
</tr>
<tr>
<td>0.22</td>
<td>10.73</td>
<td>10.2 ± 0.8</td>
<td>0.95</td>
</tr>
<tr>
<td>0.19</td>
<td>10.70</td>
<td>9.9 ± 0.1</td>
<td>0.92</td>
</tr>
<tr>
<td>0.08</td>
<td>10.58</td>
<td>10.4 ± 0.5</td>
<td>0.98</td>
</tr>
</tbody>
</table>
F Trajectory droplet after collision

As can be seen in Section 4.3, the CIJ droplet is deflected at least 2° in the impact parameter range $0.58 \leq I \leq 0.83$, and to show the trajectory of both droplets after the collision at different positions in their trajectory, Figure F 1 and Figure F 2 shows this trajectory for a collision with impact parameter $I = 0.66$.

![Figure F 1](image1)
![Figure F 1](image2)
![Figure F 1](image3)

Figure F 1 Trajectory of deflected CIJ droplet before and after collision. a) start experiment, b) $t = 360 \mu$s, c) $t = 760 \mu$s and camera is moved 1 mm downwards, d) $t = 960 \mu$s and camera is at same position as c), e) $t = 1260 \mu$s and camera is moved 5 mm downwards under initial position, f) $t = 1480 \mu$s, camera 7 mm under initial position. $v_{CIJ} = 11 \text{ m/s}$, $v_{DOD} = 1.6 \text{ m/s}$, $d_{CIJ} = 110 \mu$m and $d_{DOD} = 55 \mu$m.
Figure F 2  Trajectory of the DOD droplet after the collision. Pictures a), b) and c) from Figure F 1 are the first pictures of the trajectory, a) $t = 1260 \ \mu s$ and camera 2 mm under initial position, b) $t = 1480 \ \mu s$ and camera 2 mm under initial position. $v_{CIJ} = 11 \ \text{m/s}$, $v_{DOD} = 1.6 \ \text{m/s}$, $d_{CIJ} = 110 \ \mu m$ and $d_{DOD} = 55 \ \mu m$. 