Controlled ring-vortex injection into a turbulent pipe flow

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October 30, 2017
Controlled ring-vortex injection into a turbulent pipe flow

Master of Science Thesis

For obtaining the degree of Master of Science in Aerospace Engineering at Delft University of Technology

Christiaan Maria Sanders

October 30, 2017

Faculty of Aerospace Engineering · Delft University of Technology
The undersigned hereby certify that they have read and recommend to the Faculty of Aerospace Engineering for acceptance the thesis entitled “Controlled ring-vortex injection into a turbulent pipe flow” by Christiaan Maria Sanders in fulfillment of the requirements for the degree of Master of Science.

Dated: October 30, 2017

Supervisors:

Prof. dr. ir. Jerry Westerweel

Dr. ir. Bas van Oudheusden

Dr. ir. Gerrit Elsinga

Dr. ir. Ferry Schrijer
Before you lies the thesis “Controlled ring-vortex injection into a turbulent pipe flow”, the basis of which is an experimental study on the interaction characteristics between coherent structures in pipe flows.

Using a new, specific way of injecting, different types of large-scale coherent structures, like hairpin- and ring-vortices, can be formed. The energy interaction between these structures is studied by conducting stereoscopic particle image velocimetry measurements. In this manner, the velocity field of these structures can be investigated, to see the effect these structures have on each other and their velocity field surrounding them.

This work has been written to fulfil the graduation requirements of the Aerospace Engineering Program, in the field of Aerodynamics at Delft University of Technology. My research question was formulated together with my supervisor, Dr. Ir. G. E. Elsinga. The research has continuously required a high focus. However, conducting the experiments allowed me to answer part of the research question that we identified.

During my research, the balance between my work and study has been a turbulent, though inspiring, journey on its own. Therefore, I would like to thank my supervisors for their excellent guidance and support during this process. Fortunately, Prof. dr. ir. Jerry Westerweel, Dr. ir. Bas van Oudheusden and Dr. ir. Gerrit Elsinga were always available and willing to answer my queries.

Secondly, I would like to thank Prof. dr. ir. Gijs Ooms and Prof. dr. ir. Ruud Henkes for offering me the opportunity to work as a student assistant on the core-annular flow project, which both greatly inspired and supported me throughout the writing of my thesis. Furthermore, I wish to thank ing. Edwin Overmars, Jasper Ruijgrok and Jan Graafland, without whose cooperation I would not have been able to conduct this analysis.

Finally, I would like to thank Dr. ir. Mathieu Pourquie. It was always helpful and great fun to share ideas about my research and projects with you. I also benefited from debating issues with my fellow students and family. If I ever lost my energy, you gave me coffee, good coffee. My parents deserve a particular note of gratitude: your wise counsel and kind words have, as always, served me well.

I hope you enjoy your reading.

Carsten Sanders

Delft, October 30, 2017
List of Tables

3.1 Labview Injection parameters ...................................................... 23

4.1 Laser plane thickness variation, only one half of the beam width ............... 36

4.2 Experimental parameters $Re = 300$ .................................................. 39

5.1 Overview of the camera frame parameters .......................................... 48

5.2 Test-matrix of the $Re = 300$ set. ...................................................... 49

5.3 Test-matrix of the $Re = 15000$ and $Re = 35000$ set. ............................ 49
# Nomenclature

## Latin Symbols

<table>
<thead>
<tr>
<th>symbol</th>
<th>explanation (dimension)</th>
<th>page (eq.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{inj}$</td>
<td>injection area (m$^2$)</td>
<td>13</td>
</tr>
<tr>
<td>$A_I$</td>
<td>interrogation area (m$^2$)</td>
<td>37</td>
</tr>
<tr>
<td>$A_{pipe}$</td>
<td>cross-sectional area pipe (m$^2$)</td>
<td>47</td>
</tr>
<tr>
<td>$A_{tube}$</td>
<td>cross-sectional area tube (m$^2$)</td>
<td>48</td>
</tr>
<tr>
<td>$a$</td>
<td>ring vortex core radius (m)</td>
<td>15</td>
</tr>
<tr>
<td>$[B]_{Eu}$</td>
<td>Euler rotation matrix, about the x-axis</td>
<td>(6.3)</td>
</tr>
<tr>
<td>$b$</td>
<td>two times the Rayleigh length (m)</td>
<td>34</td>
</tr>
<tr>
<td>$C_{i}$</td>
<td>constants in the equation for the vortex distance (-)</td>
<td>15</td>
</tr>
<tr>
<td>$C_{eff}$</td>
<td>effective tracer concentration (part/m$^3$)</td>
<td>38</td>
</tr>
<tr>
<td>$D_{eff}$</td>
<td>effective pipe diameter (m)</td>
<td>(3.1)</td>
</tr>
<tr>
<td>$D_h$</td>
<td>hydraulic pipe diameter (m)</td>
<td>26</td>
</tr>
<tr>
<td>$D_{inn}$</td>
<td>inner pipe diameter (m)</td>
<td>19</td>
</tr>
<tr>
<td>$D_I$</td>
<td>linear dimension of the interrogation area (m,pix)</td>
<td>38</td>
</tr>
<tr>
<td>$D_{ij}$</td>
<td>Jacobian matrix of the velocity field (-)</td>
<td>(2.4)</td>
</tr>
<tr>
<td>$D_p$</td>
<td>pipe diameter (m)</td>
<td>12</td>
</tr>
<tr>
<td>$D_{rod}$</td>
<td>diameter of the rod of the piston (m)</td>
<td>19</td>
</tr>
<tr>
<td>$d$</td>
<td>diameter spot size (m)</td>
<td>33</td>
</tr>
<tr>
<td>$d_a$</td>
<td>diameter of the aberrated image of a point source (m)</td>
<td>36</td>
</tr>
<tr>
<td>$d_i$</td>
<td>sensor size (m)</td>
<td>31</td>
</tr>
<tr>
<td>$d_{inj}$</td>
<td>injection width (m)</td>
<td>12</td>
</tr>
<tr>
<td>$d_o$</td>
<td>object size (m)</td>
<td>31</td>
</tr>
<tr>
<td>$d_p$</td>
<td>finite diameter of the PIV particle (m)</td>
<td>36</td>
</tr>
<tr>
<td>$d_s$</td>
<td>diffraction limited spot diameter (m)</td>
<td>36</td>
</tr>
<tr>
<td>$dP$</td>
<td>pressure difference (N/m$^2$)</td>
<td>(3.9)</td>
</tr>
<tr>
<td>$d_r$</td>
<td>particle image diameter (m)</td>
<td>(4.9)</td>
</tr>
</tbody>
</table>
## Latin Symbols

<table>
<thead>
<tr>
<th>symbol</th>
<th>explanation (dimension)</th>
<th>page (eq.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$</td>
<td>kinetic energy ($m^2/s^2$)</td>
<td>11</td>
</tr>
<tr>
<td>$Eu$</td>
<td>Euler number (-)</td>
<td>(2.42)</td>
</tr>
<tr>
<td>$f$</td>
<td>shedding frequency ($s^{-1}$)</td>
<td>13</td>
</tr>
<tr>
<td>$f$</td>
<td>friction factor (-)</td>
<td>(3.12)</td>
</tr>
<tr>
<td>$f$</td>
<td>Fanning friction factor (-)</td>
<td>(6.2)</td>
</tr>
<tr>
<td>$f_{cyl}$</td>
<td>focal point cylindrical lens ($m$)</td>
<td>33</td>
</tr>
<tr>
<td>$f_D$</td>
<td>Darcy friction factor (-)</td>
<td>(3.10)</td>
</tr>
<tr>
<td>$f_s$</td>
<td>sampling frequency ($Hz$)</td>
<td>(6.4)</td>
</tr>
<tr>
<td>$f_{sph}$</td>
<td>focal point spherical lens ($m$)</td>
<td>34</td>
</tr>
<tr>
<td>$f_0$</td>
<td>base frequency ($Hz$)</td>
<td>(6.6)</td>
</tr>
<tr>
<td>$f^#$</td>
<td>lens aperture number (-)</td>
<td>36</td>
</tr>
<tr>
<td>$h$</td>
<td>sampling rate ($s^{-1}$)</td>
<td>72</td>
</tr>
<tr>
<td>$h_{inj}$</td>
<td>height of the vortex roll-up triggering flange ($m$)</td>
<td>13</td>
</tr>
<tr>
<td>$h$</td>
<td>desired laser-plane height ($m$)</td>
<td>33</td>
</tr>
<tr>
<td>$i$</td>
<td>index for $x, y, z$ (cartesian) or $u, v, w$ (velocity) (-)</td>
<td>6</td>
</tr>
<tr>
<td>$j$</td>
<td>index for $x, y, z$ (cartesian) or $u, v, w$ (velocity) (-)</td>
<td>6</td>
</tr>
<tr>
<td>$l$</td>
<td>pipe length ($m$)</td>
<td>24</td>
</tr>
<tr>
<td>$L$</td>
<td>pipe length over which pressure is measured ($m$)</td>
<td>13</td>
</tr>
<tr>
<td>$L_c$</td>
<td>characteristic length in the fifth pi term ($m$)</td>
<td>13</td>
</tr>
<tr>
<td>$M_0$</td>
<td>image magnification factor (-)</td>
<td>(4.1), (4.2)</td>
</tr>
<tr>
<td>$m$</td>
<td>mass ($kg$)</td>
<td>22</td>
</tr>
<tr>
<td>$(m_{part})_{max}$</td>
<td>maximum particle mass ($kg$)</td>
<td>(4.11)</td>
</tr>
<tr>
<td>$m_{cel}$</td>
<td>particle mass ($kg$)</td>
<td>(4.13)</td>
</tr>
<tr>
<td>$n_i$</td>
<td>medium refractive index (-)</td>
<td>34</td>
</tr>
<tr>
<td>$nrperiods$</td>
<td>number of periods of injections (-)</td>
<td>23</td>
</tr>
<tr>
<td>$N$</td>
<td>number of sample points (-)</td>
<td>72</td>
</tr>
<tr>
<td>$N_s$</td>
<td>source density ($part/m^3$)</td>
<td>(4.17)</td>
</tr>
<tr>
<td>$(N_s)_{eff}$</td>
<td>effective source density ($part/m^3$)</td>
<td>38</td>
</tr>
<tr>
<td>$N_I$</td>
<td>image density (-)</td>
<td>(4.18)</td>
</tr>
<tr>
<td>$P$</td>
<td>pressure ($N/m^2$)</td>
<td>6</td>
</tr>
<tr>
<td>$P$</td>
<td>first invariant of the velocity gradient tensor (-)</td>
<td>7, (2.6)</td>
</tr>
<tr>
<td>$P_{stag.tube}$</td>
<td>stagnation pressure injection chamber tube ($N/m^2$)</td>
<td>(5.6)</td>
</tr>
<tr>
<td>$dP$</td>
<td>pressure difference over a pipe section ($N/m^2$)</td>
<td>3.9</td>
</tr>
<tr>
<td>$p$</td>
<td>ensemble averaged pressure ($N/m^2$)</td>
<td>11</td>
</tr>
<tr>
<td>$Q$</td>
<td>second invariant of the velocity gradient tensor (-)</td>
<td>7, (2.3), (2.15)</td>
</tr>
<tr>
<td>$Q_{inj}$</td>
<td>injection mass flow ($kg/s$)</td>
<td>(5.1), (5.3)</td>
</tr>
<tr>
<td>$Q_{pipe}$</td>
<td>pipe mass flow ($kg/s$)</td>
<td>47</td>
</tr>
<tr>
<td>$Q_{tube}$</td>
<td>tube mass flow ($kg/s$)</td>
<td>(5.4)</td>
</tr>
<tr>
<td>$R$</td>
<td>third invariant of the velocity gradient tensor (-)</td>
<td>7, (2.9)</td>
</tr>
<tr>
<td>$R_{pipe}$</td>
<td>pipe radius ($m$)</td>
<td>28</td>
</tr>
</tbody>
</table>
## Latin Symbols

<table>
<thead>
<tr>
<th>symbol</th>
<th>explanation (dimension)</th>
<th>page (eq.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>ring vortex radius ($m$)</td>
<td>(3.14)</td>
</tr>
<tr>
<td>Re</td>
<td>Reynolds number based on the bulk velocity (-)</td>
<td>(2.41)</td>
</tr>
<tr>
<td>r</td>
<td>radial position from ring vortex centroid ($m$)</td>
<td>15</td>
</tr>
<tr>
<td>rc</td>
<td>circular vortex core radius ($m$)</td>
<td>15</td>
</tr>
<tr>
<td>St</td>
<td>Strouhal number (-)</td>
<td>(2.45)</td>
</tr>
<tr>
<td>$S_j$</td>
<td>rate of strain tensor ($s^{-1}$)</td>
<td>7</td>
</tr>
<tr>
<td>$S_{u_z-tot}$,$S_{u_z-tot}$</td>
<td>auto-spectral density ($mm^2s^2/Hz$)</td>
<td>(6.7)</td>
</tr>
<tr>
<td>t</td>
<td>time ($s$)</td>
<td>6</td>
</tr>
<tr>
<td>tvort.arr.</td>
<td>vortex arrival time at measurement section ($s$)</td>
<td>15</td>
</tr>
<tr>
<td>tvort.gen.</td>
<td>vortex generation time ($s$)</td>
<td>28</td>
</tr>
<tr>
<td>tvort.arr.max</td>
<td>maximum vortex arrival time ($s$)</td>
<td>(3.17)</td>
</tr>
<tr>
<td>Tact</td>
<td>single injection time ($s$)</td>
<td>23</td>
</tr>
<tr>
<td>Twait</td>
<td>time between two injections ($s$)</td>
<td>23</td>
</tr>
<tr>
<td>Tm</td>
<td>measurement time ($s$)</td>
<td>(6.5)</td>
</tr>
<tr>
<td>ub</td>
<td>bulk velocity ($m/s$)</td>
<td>47</td>
</tr>
<tr>
<td>$u_{x,y,t}$</td>
<td>in-plane velocity $x$-direction ($m/s$)</td>
<td>10</td>
</tr>
<tr>
<td>$u_i$</td>
<td>velocity components ($m/s$)</td>
<td>6</td>
</tr>
<tr>
<td>$u_{inj}$</td>
<td>injection velocity ($m/s$)</td>
<td>(3.17), (5.2)</td>
</tr>
<tr>
<td>$u'_i(x,y,t)$</td>
<td>fluctuating velocity components ($m/s$)</td>
<td>10</td>
</tr>
<tr>
<td>$u'_j$</td>
<td>Reynolds stresses ($m^2/s^2$)</td>
<td>11</td>
</tr>
<tr>
<td>$u_i(x,y,t)$</td>
<td>velocity components at $(x,y)$ and $t$ ($m/s$)</td>
<td>(2.30)</td>
</tr>
<tr>
<td>$u'_i(x,y,t)$</td>
<td>fluctuations velocity components at $(x,y)$ and $t$ ($m/s$)</td>
<td>(10)</td>
</tr>
<tr>
<td>$\overline{u}_i(x,y,t)$</td>
<td>mean velocity components at $(x,y)$ and $t$ ($m/s$)</td>
<td>(10)</td>
</tr>
<tr>
<td>$u_{piston}$</td>
<td>piston velocity ($m/s$)</td>
<td>(3.8)</td>
</tr>
<tr>
<td>utube</td>
<td>flow velocity in the injection chamber tube ($m/s$)</td>
<td>(5.5)</td>
</tr>
<tr>
<td>$u_{r}$</td>
<td>friction velocity ($m/s$)</td>
<td>(2.24)</td>
</tr>
<tr>
<td>$u_{s(1)}$</td>
<td>friction velocity ($mm/s$)</td>
<td>(6.1)</td>
</tr>
<tr>
<td>$&lt; U_x &gt;$</td>
<td>mean in-plane-velocity in x direction ($mm/s$)</td>
<td>(66)</td>
</tr>
<tr>
<td>$&lt; U_y &gt;$</td>
<td>mean in-plane-velocity in y direction ($mm/s$)</td>
<td>(66)</td>
</tr>
<tr>
<td>$&lt; U_z &gt;$</td>
<td>mean out-of-plane-velocity in z direction ($mm/s$)</td>
<td>(66)</td>
</tr>
<tr>
<td>U</td>
<td>velocity of a 3D thin cored vortex centroid ($m/s$)</td>
<td>(2.46)</td>
</tr>
<tr>
<td>$U_{Eu}$</td>
<td>3D velocity vector after Euler rotation ($mm/s$)</td>
<td>(6.3)</td>
</tr>
<tr>
<td>$U_{y,t}$</td>
<td>velocity profile over the y-direction over time ($m/s$)</td>
<td>??</td>
</tr>
<tr>
<td>$U_{\infty}$</td>
<td>free-stream velocity ($m/s$)</td>
<td>12</td>
</tr>
<tr>
<td>$u_{x,y,t}$</td>
<td>in-plane velocity $y$-direction ($m/s$)</td>
<td>10</td>
</tr>
<tr>
<td>V</td>
<td>electrical voltage ($V$)</td>
<td>24</td>
</tr>
<tr>
<td>$V_{tr.part}$</td>
<td>volume of one tracer particle ($m/s$)</td>
<td>(4.12)</td>
</tr>
<tr>
<td>$V_{water}$</td>
<td>total flow facility water volume ($m/s$)</td>
<td>37</td>
</tr>
<tr>
<td>$w_{x,y,t}$</td>
<td>out-of-plane velocity $z$-direction ($m/s$)</td>
<td>10</td>
</tr>
<tr>
<td>$w_{mean}$</td>
<td>mean out-of-plane velocity ($m/s$)</td>
<td>74</td>
</tr>
</tbody>
</table>
# Latin Symbols

<table>
<thead>
<tr>
<th>symbol</th>
<th>explanation (dimension)</th>
<th>page (eq.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$w(z)$</td>
<td>laser waist radius as a function of the $z$-coordinate ($m$)</td>
<td>34</td>
</tr>
<tr>
<td>$w_0$</td>
<td>minimum laser waist ($m$)</td>
<td>(4.5)</td>
</tr>
<tr>
<td>$x_i, x_j$</td>
<td>distance from the centre of the pipe outward ($m$)</td>
<td>6</td>
</tr>
<tr>
<td>$x$</td>
<td>distance injection location to measurement location ($m$)</td>
<td>(2.48)</td>
</tr>
<tr>
<td>$y$</td>
<td>distance from the wall for one $y^+$ unit ($m$)</td>
<td>(3.5)</td>
</tr>
<tr>
<td>$y^+$</td>
<td>wall distance in viscous wall units ($)</td>
<td>(3.2)</td>
</tr>
<tr>
<td>$z_R$</td>
<td>Raileigh length ($m$)</td>
<td>(4.6)</td>
</tr>
</tbody>
</table>
### Greek Symbols

<table>
<thead>
<tr>
<th>symbol</th>
<th>explanation (dimension)</th>
<th>page (eq.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>tilt angle of the image plane, local angle of attack ($deg$)</td>
<td>32</td>
</tr>
<tr>
<td>$\alpha_{inj}$</td>
<td>injection angle ($deg$)</td>
<td>(2.44)</td>
</tr>
<tr>
<td>$\beta$</td>
<td>bulk velocity percentage of the injection ($%$)</td>
<td>48</td>
</tr>
<tr>
<td>$\Gamma(r,t)$</td>
<td>circulation Oseen-Lamb viscous filament ($m^2/s$)</td>
<td>(2.47)</td>
</tr>
<tr>
<td>$\Gamma_0$</td>
<td>circulation at $t = 0$ ($m^2/s$)</td>
<td>15</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Scheimpflug angle ($deg$)</td>
<td>32</td>
</tr>
<tr>
<td>$\delta z$</td>
<td>focal depth of field ($m$)</td>
<td>(4.8)</td>
</tr>
<tr>
<td>$\Delta x_{rel}$</td>
<td>distance between the two lenses ($m$)</td>
<td>(4.4)</td>
</tr>
<tr>
<td>$</td>
<td>\Delta X</td>
<td>$</td>
</tr>
<tr>
<td>$\Delta P$</td>
<td>pressure drop measured over a pipe length ($N/m^2$)</td>
<td>(3.13)</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>time step ($s$)</td>
<td>72</td>
</tr>
<tr>
<td>$</td>
<td>\Delta z</td>
<td>$</td>
</tr>
<tr>
<td>$\Delta z_0$</td>
<td>light sheet thickness ($m$)</td>
<td>(4.3)</td>
</tr>
<tr>
<td>$(\Delta z_0)_{eff}$</td>
<td>effective light sheet thickness ($m$)</td>
<td>35</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>wall roughness ($mm$)</td>
<td>26</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Kolmogorov length scale ($m$)</td>
<td>21</td>
</tr>
<tr>
<td>$\theta$</td>
<td>stereoscopic viewing angle ($deg$)</td>
<td>32</td>
</tr>
<tr>
<td>$\theta$</td>
<td>half beam waist angle angle ($rad$)</td>
<td>34</td>
</tr>
<tr>
<td>$\theta_{Eu}$</td>
<td>Euler rotation angle about the y-axis ($deg$)</td>
<td>64</td>
</tr>
<tr>
<td>$\theta_i$</td>
<td>Snellius angle ($deg$)</td>
<td>34</td>
</tr>
<tr>
<td>$\Theta$</td>
<td>total beam waist angle angle ($deg$)</td>
<td>34</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>von Karman number ($-$)</td>
<td>47</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>wave length laser ($m$)</td>
<td>34</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>eigenvalue of the characteristic equation of $\nabla v$ ($m$)</td>
<td>(2.5)</td>
</tr>
<tr>
<td>$\mu$</td>
<td>dynamic viscosity ($Ns/m^2$)</td>
<td>12</td>
</tr>
<tr>
<td>$\nu$</td>
<td>kinematic viscosity ($m^2/s$)</td>
<td>6</td>
</tr>
<tr>
<td>$\pi_i^0$</td>
<td>dimensionless group of the Buckingham pi theory ($-$)</td>
<td>(2.35)</td>
</tr>
<tr>
<td>$\rho$</td>
<td>density ($kg/m^3$)</td>
<td>6</td>
</tr>
<tr>
<td>$\rho_{tr.part}$</td>
<td>density tracer particle ($kg/m^3$)</td>
<td>37</td>
</tr>
<tr>
<td>$\tau$</td>
<td>time integration parameter ($s$)</td>
<td>15</td>
</tr>
<tr>
<td>$\tau_{wall}$</td>
<td>wall shear stress ($-$)</td>
<td>(3.2)</td>
</tr>
<tr>
<td>$\tau_{sr}$</td>
<td>total shear stress in polar coordinates ($-$)</td>
<td>(2.26)</td>
</tr>
<tr>
<td>$\psi_{Eu}$</td>
<td>Euler rotation angle about the x-axis ($deg$)</td>
<td>64</td>
</tr>
<tr>
<td>$\Omega_{ij}$</td>
<td>vorticity tensor ($rad/s$)</td>
<td>6</td>
</tr>
<tr>
<td>$\omega$</td>
<td>vorticity ($rad/s$)</td>
<td>13</td>
</tr>
</tbody>
</table>
## Acronyms

<table>
<thead>
<tr>
<th>acronym</th>
<th>explanation</th>
<th>page</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMOS</td>
<td>complementary metal oxide semiconductor</td>
<td>31</td>
</tr>
<tr>
<td>CR</td>
<td>contraction ratio</td>
<td>18</td>
</tr>
<tr>
<td>FFT</td>
<td>fast Fourier transform</td>
<td>72</td>
</tr>
<tr>
<td>HSR</td>
<td>high speed resolution</td>
<td>31</td>
</tr>
<tr>
<td>IFFT</td>
<td>inverse fast Fourier transform</td>
<td>74</td>
</tr>
<tr>
<td>MKE</td>
<td>mean kinetic energy</td>
<td>11</td>
</tr>
<tr>
<td>Nd:YLF</td>
<td>Neodymium-doped Yttrium Lithium Fluoride</td>
<td>36</td>
</tr>
<tr>
<td>PIV</td>
<td>particle image velocimetry</td>
<td>2</td>
</tr>
<tr>
<td>PT</td>
<td>Platinum resistance thermometer</td>
<td>18</td>
</tr>
<tr>
<td>PVC</td>
<td>Poly Vinyl Chloride</td>
<td>20</td>
</tr>
<tr>
<td>RANS</td>
<td>Reynolds averaged Navier-Stokes equations</td>
<td>8</td>
</tr>
<tr>
<td>RC</td>
<td>remote control</td>
<td>18</td>
</tr>
<tr>
<td>RMS</td>
<td>root mean square</td>
<td>10</td>
</tr>
<tr>
<td>SNR</td>
<td>signal to noise ratio</td>
<td>74</td>
</tr>
<tr>
<td>SPIV</td>
<td>stereoscopic particle image velocimetry</td>
<td>2</td>
</tr>
<tr>
<td>UV</td>
<td>ultra violet</td>
<td>105</td>
</tr>
<tr>
<td>VLSs</td>
<td>very large scale structures</td>
<td>47</td>
</tr>
<tr>
<td>VLSMs</td>
<td>very large scale motions</td>
<td>44</td>
</tr>
</tbody>
</table>
Coherent structures, like vortices, can be used to gain understanding of complex turbulent flows. In fact, the study can provide information on a 3D velocity fields of developing coherent structures from small- to large-scales, which can be used for weather forecasts.

Classically, it is assumed that the energy cascades from large to smaller vortices, as formulated by Richardson. It was indicated by Hunt, J.C.R. (2010), that such a conceptual picture of turbulence underestimates the rates at which the structure of turbulence is adjusting. Hunt continues by stating that there is experimental evidence of a phenomena referred to as “the inverse energy cascade”, describing that the energy transfer, from large- to small-scale structures can be reversed. This phenomena is expected to happen for 2-D. However, for 3-D flows the mechanism is not self-evident.

Therefore, a non-intrusive vortex generator is created, that can control the generation and injection of large-scale coherent structures into a pipe flow, after which 3D flow measurements are conducted. The set-up is created as a means to provide essential information to an ultimate, long term research question: How is the energy of this injected vortex transferred to other scales? Before we can address this problem, we first need to create a non-intrusive way to generate a (large-scale) coherent structure into a (turbulent) pipe flow. The latter is the focus of this thesis. A design of such a ring vortex generator is presented. Then, a dye visualisation method is used, to test how the vortex generator is operating and to trace the generated vortex downstream. The 3D velocity field is obtained from the measured Stereoscopic Particle Image Velocimetry (SPIV) data. Rotation of the dye inside the core of the generated vortex is clearly recognised. The generation of the structures can be successfully controlled via a Labview program, where it is possible to generate both hairpin and ring vortices.

As a final result, a main hairpin structure is detected, which is stretched by the high momentum of the injected flow. Thereafter, a succession of multiple small-scaled entrainment hairpin structures appears. These, evenly mix the concentrated high-momentum flow at the centre of the pipe, with low-momentum flow, closer to the wall of the pipe. Finally, iso-contour plots of the velocity fields display a merge of the vortex pockets that belong to the multiple successive entrainment hairpins.

In future applications, this vortex generator will be used to study the interaction between the controlled ring-vortex structures and the turbulent structures, which acts as a model for scale interactions in turbulence.
Contents

Preface v

List of Tables vii

Nomenclature ix

Abstract xv

1 General Introduction 1

1.1 Background history .............................................. 1

1.2 Context of the project .......................................... 2

1.3 Aim and outline of the thesis ................................. 2

2 Theory 5

2.1 Governing equations ........................................... 5

2.1.1 The Navier-Stokes equations ............................ 6

2.1.2 The Taylor hypothesis .................................... 6

2.1.3 The $Q$-criterion ......................................... 6
## Contents

2.1.4 Derivations of $R$ and $Q$ as used in Matlab ........................................ 7

2.2 The Reynolds decomposition ................................................................. 8

2.2.1 The RANS-equations ........................................................................... 8

2.2.2 Determining the Root Mean Square (RMS) values .............................. 10

2.2.3 Turbulent kinetic energy ..................................................................... 11

2.3 Dimensionless numbers .......................................................................... 11

2.3.1 The Buckingham pi theorem ............................................................... 12

2.3.2 Analysing dimensionless numbers and injection parameters ............ 13

2.4 Saffman’s viscous ring vortex propagation equation ............................. 15

3 Methods ........................................................................................................ 17

3.1 Introduction to the flow facility ................................................................ 17

3.2 Ink visualisation ....................................................................................... 18

3.2.1 The injection mechanism .................................................................... 18

3.2.2 The piston configuration ..................................................................... 19

3.2.3 The vortex generator .......................................................................... 20

3.2.4 The Moody diagram ........................................................................... 23

3.2.5 Injection principle considering the interaction between small and large scales ........................................ 26

3.2.6 Forming the vortex and ensuring a homogeneous injection ............ 27

3.2.7 Determining the injection velocity using Saffman’s propagation equation ........................................ 28

4 Stereoscopic Particle Image Velocimetry .................................................. 31

4.1 Positioning the high speed resolution cameras ...................................... 31

4.1.1 The HSR cameras ............................................................................. 31

4.1.2 Determining the Scheimpflug angle .................................................. 32
## Contents

4.1.3 Calculating the light sheet thickness ........................................ 33

4.2 Optical systems, calibration procedure and the resolution .................. 33

4.2.1 Positioning the laser, lenses and mirror ........................................ 33

4.2.2 Relation between the light sheet thickness and particle concentration .. 36

4.2.3 Calibration procedure and positioning the calibration grid ................. 38

5 Flow Regimes  41  

5.1 Velocity Profiles ............................................................... 41

5.1.1 The theoretical velocity profiles .............................................. 41

5.1.2 The Coriolis effect .............................................................. 42

5.2 Subdivision of flow characteristics .............................................. 43

5.2.1 Coherent structures ............................................................ 43

5.2.2 Events .............................................................................. 46

5.3 Detecting the injection .......................................................... 47

5.3.1 The four phases in a measurement ............................................. 47

5.3.2 The mass percentage of injection .............................................. 47

5.3.3 Injection chamber feeding tubes stagnation pressure ....................... 48

6 Analysis  51  

6.1 Results of the dye visualisation ................................................... 51

6.1.1 Influential factors on the generated shape of the vortex .................. 51

6.1.2 The four phases during the dye visualisation at $Re = 15000$ ............. 53

6.1.3 Results of the dye visualisation at $Re = 300$ and $35000$ .................. 54

6.1.4 Limitations and considerations when using dye visualisation .............. 55

6.2 Results of the SPIV measurements .............................................. 56
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.2.1 Comparing Labview input with measured mean velocity SPIV values</td>
<td>56</td>
</tr>
<tr>
<td>6.2.2 Laminar results</td>
<td>57</td>
</tr>
<tr>
<td>6.2.3 Turbulent results</td>
<td>64</td>
</tr>
<tr>
<td>6.3 Performance</td>
<td>70</td>
</tr>
<tr>
<td>6.3.1 The camera software</td>
<td>70</td>
</tr>
<tr>
<td>6.3.2 Frequency of the pump</td>
<td>72</td>
</tr>
<tr>
<td>7 Discussion</td>
<td>75</td>
</tr>
<tr>
<td>7.1 Parameters that determine the characteristics of the generated vortex</td>
<td>75</td>
</tr>
<tr>
<td>7.2 Behavioural characteristics of the generated vortex</td>
<td>76</td>
</tr>
<tr>
<td>7.2.1 Velocity characteristics of the generated large-scale vortex</td>
<td>76</td>
</tr>
<tr>
<td>7.2.2 The relation between large and small scales</td>
<td>77</td>
</tr>
<tr>
<td>7.2.3 Detailed flow characteristics of the hairpin vortex</td>
<td>77</td>
</tr>
<tr>
<td>8 Conclusion</td>
<td>79</td>
</tr>
<tr>
<td>8.1 Overview of the obtained results</td>
<td>79</td>
</tr>
<tr>
<td>8.2 Outlook</td>
<td>81</td>
</tr>
<tr>
<td>8.2.1 Further thoughts</td>
<td>81</td>
</tr>
<tr>
<td>8.2.2 Recommendations</td>
<td>82</td>
</tr>
<tr>
<td>Bibliography</td>
<td>85</td>
</tr>
<tr>
<td>A Improvements to the Flow Facility</td>
<td>89</td>
</tr>
<tr>
<td>A.1 Segmentation of the pipe</td>
<td>89</td>
</tr>
<tr>
<td>A.2 The traverse of the calibration glass holder</td>
<td>90</td>
</tr>
<tr>
<td>A.2.1 The calibration glass holder</td>
<td>90</td>
</tr>
</tbody>
</table>
Chapter 1

General Introduction

1.1 Background history

The study of turbulent flows is of great importance. This is explicitly brought to the surface by the realisation that everything flows. Applications of knowledge in this field can be found in many areas like weather forecasting, mixing processes, medical purposes, cooling processes, prediction of volcano eruptions, and the study of stock market dynamics. Turbulent flows in pipes can be found at Reynolds numbers higher than 2100. Turbulence is an unsteady three-dimensional flow. This means that it has irregular or, sometimes called, chaotic behaviour (seemingly unpredictable). Its motion is characterised by vortical structures, also referred to as whirls or eddies. Furthermore, turbulence contains many different structural scales. The large scale, the macro-structure, largely depends on the specific flow geometry. Moreover, it is independent of the Reynolds number, which is referred to as scale similarity. The small-scale, the micro-structure, has a high energy dissipation. At this scale, most of the energy is turned into heat via friction. Turbulent flow is also known to be an effective mixer of mass, momentum and heat. Furthermore, it is known that high velocity gradients within the flow can cause a flow to become turbulent.

In 1883 Reynolds, proposed a criterion for the differentiation between laminar and turbulent flows. With today’s technology the perception of turbulence as an unorganised chaos is starting to change, perhaps into one in which structure can be found once again. One of the important issues in the field of turbulence is the energy transfer between turbulent structures, or more generally, the interaction between different structures. Richardson’s energy cascade, statistically formulated by Kolmogorov in 1941, indicates that energy flows from large- to small-scale structures, until it dissipates into heat via friction. However, the energy cascade contains some inconsistencies with recent observations. For example, it has been discovered that energy is also flowing from small- to large-scales. This can be observed when two smaller dust devils are merging to form a single and larger vortical structure. How energy is distributed over the different scales in turbulent flows can give great insights into what is happening in the flow and might provide us with useful information about its underlying
mechanism. Furthermore, a clearer view on the development and 3D orientation of coherent structures will provide useful information about the distribution of turbulent energy. Since Stereoscopic Particle Image Velocimetry (SPIV) is a robust method that can providing this kind of information, it is used during the experiments that are elaborated in this master thesis.

The method that was used by Leonardo da Vinci (1452-1519) to study turbulence in flows was based on the use of grass seeds, which were put into the flow to visualise the movement of these flows. Meanwhile, Leonardo drew what he saw. This method is very similar to the one that is used today. However, technology has developed and the method has been refined over the years. In Particle Image Velocimetry (PIV), the grains are replaced by $10^{-6}$ m hollow glass particles, which scatter the strongly intensified light-sheet, that is formed by a laser. That what was seen with the eyes, is now captured and stored in greater detail by two high-speed cameras. Finally, the data is post-processed by a computer into 3D images, which can then also be investigated, using 3D tools.

1.2 Context of the project

In many areas in the field of fluid dynamics, turbulent flows occur and coherent structures are present. For instance, vortical structures that are created by pumps can impinge onto the wall of pipes, where they will damage the pipe internally. Mixing processes profit from the turbulent energy that coherent structures poses. Also the forming of weather tornadoes can be better understood, knowing how the turbulent energy is increased by the influence of small-scale structures. Therefore, in this thesis, an attempt is made to investigate the interaction, between small- and large-scale structures, in fully developed turbulent pipe flows. Some other questions that rise are: ”Which other parameters influence the created structures?” and ”How do they behave in the flow?” . Also ”What are the velocity characteristics inside a coherent structure?” and ”How are structures related to each other?”. Furthermore: ”Can the velocity field closer to, and inside, a coherent vortex structure be better defined?”

1.3 Aim and outline of the thesis

The aim of the project is to develop a method to modify or introduce large-scale flow structures in turbulent pipe flow. Ultimately, we want to study the effect of these structures on other turbulent structures to examine their interaction and energy exchange. This research is expected to provide insight in these processes and the possibilities to control the flow. Therefore the most influential feature of turbulent flows is studied, the coherent structure. The theory, in which an overview of the governing equations is given, provides helpful information about the understanding of the position of the injected structures in space and time and is outlined in chapter 2. The methods that are used to tackle the research questions are presented in chapter 3. To study the interaction between small- and large-scale structures, a product needs to be created, that could generate large-scale structures. At the same time it should be non-intrusive for the upstream. In chapter 3, the flow facility, in which
1.3 Aim and outline of the thesis

This product is placed, is first introduced, after which aspects of the different sections of the injection mechanism are highlighted. This chapter furthermore contains sections concerning the quality of the pipe flow and the formation of the vortex in sections 3.2.4, 3.2.5, 3.2.6 and 3.2.7. Chapter 4 is solely devoted to stereoscopic particle image velocimetry, since all relevant parameters of the experimental set-up are determined and explained in it. In chapter 5, the reader is given some insight into the change of flow characteristics and events, when changing the flow from laminar into turbulent. It is shown how these changes influence the design parameters of the injection. Thereafter, in chapter 6, the results of the experiments are analysed. It is subdivided into a section for the ink visualisation and a section on the stereoscopic particle image velocimetry results. The discussion and a conclusion with a short outlook is provided in chapters 7 and 8 respectively. For further reading, Appendix A will continue with the improvements that are made to the flow facility. It contains more detailed information about the objects, that are used throughout the experiments and includes an image of the vortex generator in figure A.6. Appendix B contains an explanation on how the flow facility has to be disassembled, for the cleaning of its pipes and how the sealing of the laser cooler can be improved to prevent the danger of leaking of water inside this high powered unit. Finally, the Bibliography and the Appendix are providing information, about the references and derivations and figures respectively.
In this chapter the governing equations that describe the motion of turbulent flows are outlined. Using the Taylor hypothesis, quantities as $Q$ and $R$ are derived from these equations and are used to indicate and visualise the vortical structures in 3D. Thereafter, a Reynolds decomposition is made to indicate which quantities are important to measure. Furthermore, the Buckingham pi theorem is used to derive dimensionless relations between parameters that play a vital role in the understanding of the generation and shedding mechanism of the vortex generator. Finally, Saffman’s viscous ring propagation equation is presented. It is used to show how the estimated arrival time, of the generated vortex at the test section, can be determined as a function of the distance between the test section and the vortex generator.

### 2.1 Governing equations

![Figure 2.1: The signconvention with $z$ pointing in downstream direction.](image)

Figure 2.1 functions as a reference of the sign-conventions, that are used throughout this work, for the positions and velocities.
2.1.1 The Navier-Stokes equations

The flow in pipes is described by the Navier-Stokes equations. In this section, the facts and assumptions about the pipe flow are highlighted. The incompressible Navier-Stokes equations, in Cartesian coordinates, are given by equations (2.1) and (2.2).

\[
\frac{\partial u_i}{\partial x_i} = 0 \quad (2.1)
\]
\[
\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial P}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_j^2} \quad (2.2)
\]

Equations (2.1) and (2.2) are known as the continuity and momentum equations respectively. These two equations apply in our analysis, since the working fluid i.e. water is incompressible, the pipe thermally isolated and no heating is applied. In both of these equations the Einstein summation convention is used.

2.1.2 The Taylor hypothesis

Following Taylor, in case the velocity of a stream, which carries the swirling of a fluid known as eddies, is much greater than the turbulent velocity, one may assume that the sequence of changes in \( u \), at a fixed point, are simply due to the passage of an unchanging pattern of turbulent motion over that fixed point\(^\text{10}\). In other words, the advection of the turbulent coherent structures past a fixed point can be taken to be entirely due to the mean flow, as if the structures would be frozen. Therefore, this hypothesis is also known as the "frozen" turbulence hypothesis. Expressed into equations the hypothesis holds for \((u' / U << 1)\)\(^\text{10}\), in which \( U \) is the bulk velocity and \( u' \) the eddy velocity. Then, the substitution \( t = -z / U \) is a good approximation.

The Taylor hypothesis can be used throughout the measurements. The measurements are taken at one \( x \)-position, where an entire cross-sectional plane is obtained. In this way the coherent structures are "scanned" as they are advected downstream, as if they would be solid bodies. Thereafter, the regions with an equal value for \( Q \), referred to as the iso-\( Q \) values of a plane, are connected to from plane to plane, to reconstruct the volumetric shape of the coherent structures.

2.1.3 The \( Q \)-criterion

\( Q \)-criterion following Hunt

The \( Q \)-criterion defines a vortex as a spatial region, where

\[
Q = \frac{1}{2}(||\Omega_{ij}||^2 - ||S_{ij}||^2) > 0 \quad (2.3)
\]
2.1 Governing equations

i.e. where the Euclidean norm of the vorticity tensor dominates that of the rate of strain. Here, it is assumed that the three-dimensional velocity field \( \mathbf{v}(x, t) \) is smooth. Then, the Galilean-invariant vortex criteria can use the velocity gradient decomposition, which is also known to be the Jacobian matrix of the velocity field\(^{11}\).

\[
\nabla \mathbf{v} = D_{ij} = S_{ij} + \Omega_{ij} \tag{2.4}
\]

Where \( D_{ij} = \frac{\partial u_i}{\partial x_j}, S_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \) is the rate of strain tensor and \( \Omega_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i} \right) \) is the vorticity tensor. The characteristic equation for \( \nabla \mathbf{v} \) is known as\(^{12}\)

\[
\lambda^3 + P \lambda^2 + Q \lambda + R = 0 \tag{2.5}
\]

Where \( P, Q \) and \( R \) are the 3 invariants of the velocity gradient tensor. They are defined in equation (2.6), (2.7) and (2.8) respectively.

\[
P = -tr(D) \tag{2.6}
\]

\[
Q = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} \frac{\partial u_j}{\partial x_i} \right) = \frac{1}{2} \left( \Omega_{ij} \Omega_{ij} - S_{ij} S_{ij} \right) = \frac{1}{2} \left( ||\Omega||^2 - ||S||^2 \right) \tag{2.7}
\]

\[
R = -det(D) \tag{2.8}
\]

Where \( || \cdot || \) is defined as the Euclidean (or Frobenius) matrix norm and the swirling strength \( \lambda^2 \) as the squared magnitude of the imaginary part of the complex eigenvalues\(^{13}\). Complex eigenvalues give spiralling phase diagrams, that indicate the swirling motion of a vortex.

2.1.4 Derivations of \( R \) and \( Q \) as used in Matlab

The derivation of the vortex stretching ”\( R \)” is relatively easily done by taking the negative determinant of the \( D \) matrix. \( \mathcal{R} \) is calculated in Matlab and used to indicate stretching of the vortex ring. It is defined in equation (2.9).

\[
\mathcal{R} = \frac{\partial u_i}{\partial x} \left( \frac{\partial v}{\partial y} \frac{\partial w}{\partial z} - \frac{\partial w}{\partial y} \frac{\partial v}{\partial z} \right) + \frac{\partial u_j}{\partial y} \left( \frac{\partial v}{\partial x} \frac{\partial w}{\partial z} - \frac{\partial w}{\partial x} \frac{\partial v}{\partial z} \right) - \frac{\partial u_i}{\partial z} \left( \frac{\partial v}{\partial x} \frac{\partial w}{\partial y} - \frac{\partial w}{\partial x} \frac{\partial v}{\partial y} \right) \tag{2.9}
\]

For \( Q \) the Navier-Stokes equations are revisited. The second term on the left hand side of equation (2.2) can be rewritten in the form

\[
u_j \frac{\partial u_i}{\partial x_j} = \frac{\partial u_j u_i}{\partial x_j} - u_i \frac{\partial u_j}{\partial x_j} \tag{2.10}
\]

When neglecting the viscous second-order terms and knowing that the last term in equation (2.10) is equal to zero for incompressible flows, the momentum equation is now rewritten into
the incompressible Euler equations.

\[ \frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = -\frac{1}{\rho} \frac{\partial P}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_j^2} \]  

(2.12)

(2.13)

When taking the first derivative of equation (2.12) and neglecting the viscous term, the relation between \( Q \) and the pressure, and how it can be used to indicate a structure, becomes clear.

\[ \frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = -\frac{1}{\rho} \frac{\partial^2 P}{\partial x_i^2} \]  

(2.14)

Equation (2.14) indicates, that for a \( Q > 0 \), the pressure must be at a minimum, since \( -\frac{1}{\rho} \frac{\partial^2 P}{\partial x_i^2} > 0 \) is indicating a minimum in pressure, as \( \frac{\partial^2 P}{\partial x_i^2} < 0 \). Therefore, this criterion indicates whether or not one of the main characteristics of a vortex is present\(^\text{14}\). In the Matlab code, equation (2.15) is used to determine the value of \( Q \).

\[ Q = \left[ \frac{\partial u}{\partial y} + \frac{\partial u}{\partial z} + \frac{\partial v}{\partial y} + \frac{\partial v}{\partial z} - \frac{\partial v}{\partial x} \frac{\partial u}{\partial y} - \frac{\partial v}{\partial z} \frac{\partial u}{\partial z} - \frac{\partial w}{\partial x} \frac{\partial u}{\partial z} \right] \]  

(2.15)

### 2.2 The Reynolds decomposition

For the study of flows inside pipes, it is a custom to use cylindrical coordinates. In this section, the 3D Navier-Stokes equations are given in polar coordinates. Furthermore, the relation for the shear stress, expressed as a function of the radius of the pipe, is given.

#### 2.2.1 The RANS-equations

To find the relation of the shear stress, as a function of the pipe radius, Reynolds Averaging is applied to the Navier-Stokes equations. Thereafter, these equations are renamed, as the Reynolds Averaged Navier-Stokes, or RANS equations. The incompressible continuity and momentum equations, for the radial and axial velocities \( u_r \) and \( u_z \) respectively, are expressed...
in cylindrical coordinates in the form:

\[
\frac{1}{r} \frac{\partial r u_r}{\partial t} + \frac{1}{r} \frac{\partial u_\theta}{\partial \theta} + \frac{\partial u_z}{\partial z} = 0 \quad (2.16)
\]

\[
\frac{1}{r} \frac{\partial u_r}{\partial r} + \frac{u_\theta}{r} \frac{\partial u_r}{\partial \theta} + u_z \frac{\partial u_r}{\partial z} - \frac{u_r^2}{r} = \quad (2.17)
\]

\[
- \frac{1}{\rho} \frac{\partial P}{\partial r} + \nu \left[ \frac{1}{r} \frac{\partial}{\partial r} \left( \frac{r \frac{\partial u_r}{\partial r}}{r^2} \right) + \frac{1}{r^2} \frac{\partial^2 u_r}{\partial \theta^2} + \frac{\partial u_r^2}{\partial z^2} - \frac{u_r}{r^2} - \frac{2}{r^2} \frac{\partial u_\theta}{\partial \theta} \right]
\]

\[
\frac{\partial u_r}{\partial t} + u_r \frac{\partial u_r}{\partial r} + \frac{u_\theta}{r} \frac{\partial u_r}{\partial \theta} + u_z \frac{\partial u_r}{\partial z} = \quad (2.18)
\]

\[
- \frac{11 \frac{\partial P}{\rho}}{\partial r} + \nu \left[ \frac{1}{r} \frac{\partial}{\partial r} \left( \frac{r \frac{\partial u_\theta}{\partial r}}{r^2} \right) + \frac{1}{r^2} \frac{\partial^2 u_\theta}{\partial \theta^2} + \frac{\partial u_\theta^2}{\partial z^2} - \frac{u_\theta}{r^2} - \frac{2}{r^2} \frac{\partial u_r}{\partial \theta} \right]
\]

\[
\frac{\partial u_\theta}{\partial t} + u_r \frac{\partial u_\theta}{\partial r} + \frac{u_\theta}{r} \frac{\partial u_\theta}{\partial \theta} + u_z \frac{\partial u_\theta}{\partial z} = \quad (2.19)
\]

Where \( r, \theta \) and \( z \) are the radial, angular and axial coordinates respectively. The relation of the shear stress as a function of the pipe radius can be derived from these equations. Taking the momentum equation in the \( z \)-direction, the three non-linear terms on the left-hand-side of the equation can be rewritten. Thereafter, equations (2.16) and (2.19) are simplified by applying that the flow is:

- Statistically stationary (\( \frac{\partial}{\partial t} = 0 \))
- No mean flow in \( \theta \)- and \( r \)-direction
- Homogeneous flow in \( \theta \)- and \( z \)-direction (\( \frac{\partial}{\partial \theta} = 0 \) and \( \frac{\partial}{\partial z} = 0 \))

As a means to study turbulence, Reynolds made a decomposition of the flow, in which \( \bar{u}_i \) is known as the mean and \( u_i' \) the fluctuating part of the flow\(^{15}\).

\[
u = \bar{u}_i + u_i' \quad (2.20)
\]

The Reynolds decompositions are substituted into the \( z \)-momentum equation and the Reynolds Conditions, as displayed in Appendix C.2, are applied. Thereafter, the continuity equation is simplified by applying the homogeneous flow conditions, in combination with the boundary condition that \( u_r = 0 \) at \( r = R \), which gives:

\[
\bar{u}_r = 0 \quad \forall \ r \quad (2.21)
\]

Furthermore, it is known that the mean of a velocity fluctuations is equal to zero, but not necessarily the product of two velocity fluctuations. Applying this knowledge to the \( z \)-momentum equation will give equation (2.22).

\[
0 = \frac{-1}{\rho} \frac{\partial P}{\partial z} + \nu \frac{\partial}{\partial r} \left( \frac{r \frac{\partial \bar{u}_z}{\partial r}}{r} \right) - \frac{1}{r} \frac{\partial r u_r u_r}{\partial r} \quad \text{Reynolds-stress} \quad (2.22)
\]
Integrating equation (2.22) over the entire cross-section and using that \( u'_z = u'_r = 0 \) at the wall will give the relation:

\[
\frac{1}{\rho} \frac{\partial P}{\partial z} R = -2\nu \left( \frac{\partial u'_z}{\partial r} \right)_{r=R} \tag{2.23}
\]

The definition of the wall friction velocity given in equation 2.24.

\[
u^2 = -\nu \left( \frac{\partial u}{\partial r} \right)_{r=R} \tag{2.24}
\]

Substitution of equation (2.24) into (2.23) gives a useful expression between the pressure drop and the wall friction velocity, which is given in equation (2.25).

\[
\frac{\partial P}{\partial z} = \frac{-2\rho}{R} u'_z^2 \tag{2.25}
\]

Rewriting equation (2.22), by making use of the expression for the total shear stress, which is defined by equation (2.26), produces equation (2.27).

\[
\frac{\tau_{\tau r}}{\rho} = \nu \left( \frac{\partial u'_z}{\partial r} - u'_z u'_r \right) \tag{2.26}
\]

\[
\frac{\partial P}{\partial z} = \frac{1}{r} \frac{\partial}{\partial r} \left\{ r \tau_{\tau r} \right\} \tag{2.27}
\]

Integrating equation (2.27) with respect to \( r \), using the relation obtained in equation (2.25) and using that the boundary condition at \( r = R \), which is stated in equation (2.21), gives that \( \tau_{\tau r} = 0 \) at \( r = R \) and that the integration constant equals \( \rho u'_z^2 \). Finally, this provides the expression for the shear stress \( \tau_{\tau r} \), as a function of the radius \( r \).

\[
\tau_{\tau r} = \rho u'_z^2 \left( 1 - \frac{r}{R} \right) \tag{2.28}
\]

Or, expressed in the stress components:

\[
\frac{\rho \nu}{r} \frac{\partial u'_z}{\partial r} - \frac{\rho u'_z u'_r}{r} = \rho u'_z^2 \left( 1 - \frac{r}{R} \right) \tag{2.29}
\]

where the first and the second term on the left hand side of the equation are the viscous stress and the turbulent stress, and \( R \), the maximum value of the radius \( r \), which is equal to the pipe radius.

### 2.2.2 Determining the Root Mean Square (RMS) values

The instantaneous 3D velocity components can be written as:

\[
u_i(x,y,t) = < u_i(x,y,t) > + u'_i(x,y,t) = \begin{bmatrix}
< u(x,y,t) > + u'_i(x,y,t) \\
< v(x,y,t) > + v'_i(x,y,t) \\
< w(x,y,t) > + w'_i(x,y,t)
\end{bmatrix} \tag{2.30}
\]
2.3 Dimensionless numbers

Where \( < u_i(x,y,t) > = \bar{u}_i(x,y,t) \) are the mean velocities and \( u'_i(x,y,t) \) the velocity fluctuations respectively. In general, the RMS of the velocity fluctuations can be expressed as:

\[
\sqrt{(u_i - \bar{u}_i)(u_j - \bar{u}_j)} = \sqrt{u_i u_j - \bar{u}_i \bar{u}_j - \bar{u}_i u_j + \bar{u}_i \bar{u}_j} \tag{2.31}
\]

\[
= \sqrt{u_i u_j - \bar{u}_i \bar{u}_j - \bar{u}_i u_j + \bar{u}_i \bar{u}_j} \tag{2.32}
\]

\[
= \sqrt{\frac{u_i u_j}{\text{term 1}} - \frac{\bar{u}_i \bar{u}_j}{\text{term 2}}} \tag{2.33}
\]

In the first term, \( u_i \) and \( u_j \) are first multiplied inside the loop, in which their product for each used file is summed. Afterwards, this sum is divided by the total number of used files. In the second term however, the mean of \( u_i \) and \( u_j \) is first separately calculated. Finally, the square root of the difference between the two terms is taken.

2.2.3 Turbulent kinetic energy

The expression for the Mean Kinetic Energy (MKE) \( \overline{E} = \frac{u_i^2}{2} \) can be derived by multiplying the mean momentum, with \( \bar{u}_i \), while rewriting the diffusion term and the Reynolds term. This will produce equation 2.34.

\[
\frac{\partial \bar{E}}{\partial t} + u_j \frac{\partial \bar{E}}{\partial x_j} = -\frac{\bar{u}_i}{\rho} \frac{\partial \overline{\rho}}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \nu \frac{\partial \bar{E}}{\partial x_j} - \overline{u'_i u'_j} \right) + \overline{u'_i u'_j} \frac{\partial \bar{u}_i}{\partial x_j} - \nu \left( \frac{\partial \bar{u}_i}{\partial x_j} \right)^2 \tag{2.34}
\]

Where term 1, 2, 3 and 4 on the right hand side of equation (2.34) are known as the energy production by work, since this flow is pressure driven, the spatial redistribution of energy, by viscous and turbulent diffusion, the loss of energy, by work of the Reynolds shear stress and the loss of energy, by viscous dissipation respectively. Therefore, measuring velocity gradients and changes of the velocity fluctuations is of main importance for the understanding of energy transfer within the flow.

2.3 Dimensionless numbers

To increase the understanding of the experimental set-up and its characteristics a dimensional analysis is performed. This creates an overview and insight in what the relevant dimensionless numbers in the experiment are.

During this analysis, the pressure is taken as one of the important parameters, as it drives the flow to its velocities. Furthermore, the geometry in which the fluid is flowing and the properties of the flow itself are parameters that largely influence the shape of the generated vortical structures in it. Therefore, the following parameters are used in this analysis. The
pressure $P$, the bulk- and injection-velocity, $U_b$ and $u_{inj}$ respectively, the pipe diameter $D_p$, and the injection width $d_{inj}$, the kinematic viscosity $\mu$ and the density $\rho$ of the fluid and finally the vorticity $\omega$.

2.3.1 The Buckingham pi theorem

The dimensionless parameters are derived, using the Buckingham pi theorem.

$$\pi_0^i = U_b^{a_1} D_p^{a_2} \mu^{a_3} \rho^{a_4} P^{a_5} \sigma_{inj}^{a_6} u_{inj}^{a_7} \omega^{a_8}$$

The dimensions of these quantities are put into a matrix, for which the first row represents the time $T$. The second and third row represent the length $L$ and mass $M$ respectively. This matrix is put equal to zero, since the $\pi$ is dimensionless. The augmented matrix is row reduced so that the coefficients can be solved.

$$\begin{bmatrix} -1 & 0 & -1 & 0 & -2 & 0 & -1 & -1 & 0 \\ 1 & 1 & -1 & -3 & -1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \end{bmatrix} \sim$$

$$\begin{bmatrix} 1 & 0 & 0 & -1 & 1 & 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & -1 & -1 & 1 & 0 & -1 & 0 \\ 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \end{bmatrix}$$

This system leads to equations (2.36), (2.37), (2.38) and (2.39).

$$a_1 = a_4 - a_5 - a_7 - a_8$$  \hspace{1cm} (2.36)
$$a_2 = a_4 + a_5 - a_6 + a_8$$  \hspace{1cm} (2.37)
$$a_3 = -a_4 - a_5$$  \hspace{1cm} (2.38)
$$a_4 = a_5 = a_6 = a_7 = a_8 = free$$  \hspace{1cm} (2.39)

This result is rewritten in the following form:

$$a = \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \\ a_6 \\ a_7 \\ a_8 \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ -1 \\ 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} -1 \\ 1 \\ -1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1 \\ 0 \\ 0 \\ 1 \end{bmatrix} + \begin{bmatrix} -1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

(2.40)
2.3 Dimensionless numbers

Substitution of each vector separately, as a solution for the coefficients in equation (2.35), will lead to its corresponding dimensionless group $\pi_i^0$.

$$\pi_1 = \frac{U_b D_p \rho}{\mu} = \frac{U_b D_p}{\nu} = Re_b$$  \hspace{1cm} (2.41)

$$\pi_2 = \frac{D_p \rho}{U_b \mu} = \frac{U_b D_p \rho}{\nu \rho U_b^2} = Re_b Eu$$  \hspace{1cm} (2.42)

$$\pi_3 = \frac{d_{inj}}{D_p}$$  \hspace{1cm} (2.43)

$$\pi_4 = \frac{u_{inj}}{U_b} = \tan (\alpha_{inj})$$  \hspace{1cm} (2.44)

$$\pi_5 = \frac{D_p \omega}{U_b} = \frac{D_p 2\pi f}{U_b} = \frac{D_p 2\pi f L}{U_b} = \frac{D_p 2\pi}{h_{inj}} St$$  \hspace{1cm} (2.45)

2.3.2 Analysing dimensionless numbers and injection parameters

The first pi term in equation (2.41) is recognised as the Reynolds number ($Re$) that represents the ratio between the inertial and viscous forces. This number is used to indicate whether a flow is laminar or turbulent. For the second pi term given in equation (2.42) a combination of two dimensionless numbers is recognised. The dimensionless group that appears newly is known as the Euler number ($Eu$). It represents the ratio between the local pressure drop e.g. over for instance a pipe length and the kinetic energy per volume. It is used to characterize losses in the flow, for instance due to friction. Therefore, it is obvious that this number can be coupled to the Reynolds number for incompressible flow. The relation between the Reynolds number and the Euler number can be found in a Moody diagram (figure 3.6(a)), here the friction factor can be expressed as $\frac{2D_p}{L} Eu$, where $L$ is the length over which the pressure measurement is conducted to produce the Moody diagram in section 3.2.4. The third pi term in equation (2.43) is the ratio between the injection slit width and the inner diameter of the pipe, which is equal to 1/80 for the present experiment. They are both linked to each other via the equation for the injection area $A_{inj} = \pi D_p d_{inj}$, which is linked to the maximum injection velocity, that is defined in tables 5.2 and 5.3, for the Reynolds number under which the experiments are conducted. The fourth pi term, defined in equation (2.44), is the ratio between the injection velocity and the bulk velocity. These velocities are perpendicular with respect to each other. Therefore, their ratio will be equal to the tangent of the angle $\alpha_{inj}$, by which the upstream velocity vector is deflected from the wall to the center of the pipe during an injection. In the last pi term, which is given by equation (2.45), $h_{inj}$ is defined as the height of the flange over which the injected fluid will be triggered into a vortex roll-up, just before entering the pipe. Furthermore, the Strouhal number ($St$) is recognised. It is often used to characterise oscillating flows. In this expression, $f$ is the frequency of vortex shedding, $L$ is the characteristic length and $U_b$ the bulk velocity.

During this analysis it is used that $\omega = 2\pi f$, in which it is assumed that this $\omega$ is realised by a circular vortex core, with radius $r_c$. Assuming that the vortex rotation is similar to a solid body rotation, $\omega = \frac{2u_{inj}}{r_c}$. Therefore, the injection velocity $u_i$ can be linked to the shedding frequency $f$ and the core radius $r_c$ of the shedded vortex. In Aerospace
engineering the Strouhal number is used in certain cases like heaving (plunging) flight, where the characteristic length $L$ is the amplitude of oscillation. Since the injected flow is triggered to circulate around the local fringe, this parameter is linked to the fringe height of the vortex generator. It has to be noted that the "plunging effect" on a wing, in the aerospace case, strongly depends on the change in angle of attack. In our case this angle of attack is changed since it is determined by $\alpha_{inj} = \arctan \left( \frac{u_{inj}}{U_b} \right)$, for which the injection velocity $u_{inj}$ is decreasing in time as displayed in figure 2.2 and 6.4(b), in section 6.2.1.

![Diagram](image)

(a) Vortex generation at $t = 0$, where the injection velocity is shielding the vortex from the upstream flow.

(b) Vortex generation at $t = 0 + \Delta t$, here the injection velocity has decreased and the vortex is shed.

**Figure 2.2:** Vortex shedding at the injection location, due to the change of injection angle $\alpha_{inj}$ at $Re = 15000$.

A smaller $\alpha_{inj}$, means that the generated vortex will experience a dynamic pressure that will shed it from its injection location. Therefore, it is assumed that the change in $\alpha_{inj}$ behind the flange will be one of the main parameters responsible for the shedding of the generated vortex. Accordingly, the choice is made to vary the injection velocity in the following way. To ensure that the vortex has time to be generated, the start-up injection velocity has a high acceleration with respect to the later stages of injection. In such way, it forms an isolated low-velocity region in which the vortex can develop. Shortly after, the injection velocity is steadily decreased, this separates the vortex from the injection location and propagates it to the center of the pipe as indicated in figure 2.2(b). At this stage the angle $\alpha_{inj}$ is decreased even further and the shedding of the structure is completed. Other influential factors on the injection velocity, as an air bubble inside the injection chamber, are discussed in section 6.1.1.
2.4 Saffman’s viscous ring vortex propagation equation

The expression for the decay of the velocity of a self-propulsive, viscous, ring vortex is given by equation (2.46)\textsuperscript{17}.

\[ U = \frac{\Gamma_{r,t}}{4\pi R} \left[ \log \frac{8R}{\sqrt{4\nu t}} - 0.558 \right] \quad (2.46) \]

Where \( U \), is the velocity in time \( t \) of a three-dimensional, thin cored, vortex centroid with circulation \( \Gamma \), ring radius \( R \) and core radius \( a \) \((a/R \ll 1)\) in a Newtonian fluid, with kinematic viscosity \( \nu \). Furthermore, in the derivation of equation (2.46), the distribution of circulation corresponding to the Oseen-Lamb viscous filament is used. This expression is given in equation (2.47)\textsuperscript{17}.

\[ \Gamma(r,t) = \Gamma_0 (1 - e^{-r^2/4
u t}) \quad (2.47) \]

These equations are used to obtain the injection velocity, corresponds to the vortex that is measured at the test section at a specific time. This method is explained in section 3.2.7. Using equation (2.46), the group velocity of the vortex is measured at the test section. \( R \) and \( \Gamma \) can also be determined at that location. When ”frozen turbulence” is assumed \((\Gamma = Const)\) and when equation (2.46) is integrated over time this will give equation 2.49.

\[ x = C_1 \int_{t=t_0}^{t=t_1} \log \left( \frac{C_2}{\sqrt{\tau}} \right) d\tau \quad (2.48) \]

\[ \Rightarrow x = C_1 \left( \frac{t}{2} \right) + t \log \left( \frac{C_3}{\sqrt{t}} \right) + C_3 \quad (2.49) \]

Where \( C_1 = \frac{\Gamma}{4\pi R}, \ C_2 = 8R4^{-1/2}\nu^{-1/2}, \ C_3 = x_0, \ t_{\text{vort.arr.}} = t_1 - t_0 \) and \( x \) the travelled distance between the vortex generator and the test section at the location of the laser plane. Furthermore, \( t_{\text{vort.arr.}} \) is defined as the vortex arrival time.
Chapter 3

Methods

In this chapter the methods are discussed so that a ring vortex can be generated and a study can be made on the interaction with its environment. However, a separate chapter is devoted to the SPIV method. The SPIV method is a, more complex, method and is therefore elaborated on in chapter 4.

3.1 Introduction to the flow facility

The Experiments are conducted in the pipe flow facility of Fluid Dynamics at the faculty of 3ME at Delft University of Technology. Its configuration is shown in figure 3.1. In the summer of 2000 the originally 34 m long pipe was changed to a length of 28 m to let it fit into its new location. This has changed some of the flow-characteristics in the pipe. Its orientation changed from principally North-South to East-West. This resulted in an increase in skewness of the laminar velocity profile due to an increase of the outer product between the Earth rotation vector and the velocity vector.

Figure 3.1: A modified version of the schematic overview of the flow facility that was created by C. van Doorne.18
From left to right the water in the reservoir, of figure 3.1, is pumped through the system by the present centrifugal pump. This pump replaced the former disc-pump, that was used when working with polymer solutions. The frequency of the pump is regulated by a frequency regulator, that can be operated both locally and by means of a Remote Control (RC). From the pump, the water is entering the settling chamber. To avoid thermal convection, this chamber consists of two different settling chambers. One with Contraction Ratio (CR) equal to 39 and a smaller one placed within it, that has a CR equal to 9. Water is circulated in the space between these two settling chambers for the thermal insulation. Thereafter, the water flows through its 28 m long pipe, which has an inner diameter of 40 mm. The outer side of the pipe is covered by grey foam that insulates it thermally. Furthermore, it keeps algae from growing inside the pipes. In this way a constant water-temperature is assured during the conduction of measurements. Then the water will pass the disturbance generator, after which its evolution is investigated in the test section by means of the SPIV system. Via the insertion tank that is located after the test section, the pipe can be opened for inside cleaning of the test section. During the calibration procedure this entrance is used to insert the calibration grid into the test section. By means of a magnetic inductive flow meter, produced by Krohne-Altometer, the mean flow rate is measured at its successive stage. Thereafter, its temperature is measured by a Platinum resistance thermometer (PT100), in order to determine the kinematic viscosity so that the Reynolds number can be derived. Thenceforth, the flow will pass a valve before it will enter the discharge chamber. At this location the PIV particles can be added to the flow for measurements. The return pipe connects the discharge chamber to the water reservoir what is making it a closed system. Further details about the pipe flow facility can be found in other work. During measurements the flow speed is manually and remotely controlled without a feedback loop. Variations in the flow rate were in the order of 3% of the mean flow rate and have a time scale of about 15 to 20 seconds. The thermometer can measure the temperature with 0.2 accuracy.

3.2 Ink visualisation

3.2.1 The injection mechanism

An amount of 1 g/l cobalt blue ink is solved in water to visualise the generated vortex during the injections of the water into the pipe. The system that is used to supply this water to the injection mechanism consists of a motor that drives a traverse, which in turn will move two pistons that simultaneously inject and insert water as illustrated in figure 3.2. The script that controls the motor output is written in a Labview program on the computer. During the operation of the injection mechanism only an outflow is desired. To fulfil this requirement, a design is made that includes check valves, which is displayed in figure 3.2(b). Also the check valves are indicated by an arrow symbol. Furthermore, the green trajectory in figure 3.2(b) is indicating the collected output of both pistons and the red part their combined intake. For each stroke these paths alternate side. This is made possible by using the check valves to isolate the intake and output of water that is taking place at the same time in the different chambers of each pump. This gives the opportunity to inject with a higher frequency to study for instance the interaction between two injected structures. At a later stage of the SPIV
3.2 Ink visualisation

(a) Schematic overview of (1) the motor, (2) the gear wheel, (3) position indicator, (4) strap, (5) traverse, (6) hoses and (7) the pistons.

(b) Schematic of the pump-system with simultaneously water in- and output.

Figure 3.2: The water supply mechanism.

measurements the ink reservoir is replaced by a direct connection to the discharge chamber via a longer hose, with an enlarged diameter to reduce pressure drop. Further information about the shape of the created coherent structures and the mass percentage of the injection is found in chapter 6 and section 5.3 respectively.

3.2.2 The piston configuration

Each piston contains two chambers. The volume of the chamber that contains the piston rod is smaller. The smaller chamber has an inner diameter $D_{inn}$, including the area of the piston rod with diameter $D_{rod}$. Only chamber combinations that create outflow are investigated. Then the effective diameter $D_{eff}$ is calculated of this combination. Figure 3.3 displays all four possible configurations. Equation (3.1) is providing the effective diameter for the case that the small and large chambers are connected to inject and absorb at the same time. Connecting both left and right chambers of the pistons obtains a maximum and equal volume during each stroke. Therefore, configuration 1 is chosen for the experiment.

$$D_{eff} = \sqrt{D_{inn}^2 + (D_{inn}^2 - D_{rod}^2)} = \sqrt{25^2 + (25^2 - 10^2)} = 33.9 \text{ mm} \quad (3.1)$$
3.2.3 The vortex generator

The injection chamber that was used by C. van Doorne contained a porous tube of 50 mm in length that run over the length of the pipe. Over this total length the fluid would be injected. Since this length would have an effect on the sharpness of the injection, part of this porous tube is covered with foil during the first attempt to generate a single vortex. Thereafter, it is put back into the injection chamber. This procedure was followed to minimise any modifications that had to be made to the injection chamber that was created by C. van Doorne. The injection is done only over one centimetre of distance along the cylinder wall. As a result a diffused puff was generated. The diffusivity of injection direction, which is created by the low control of the direction of the holes in the porous wall could have been the cause of this problem. Furthermore, the injection is conducted over a relatively broad location which might destabilise any newly formed structures. In addition, the height of the injection chamber decreases linearly in downstream direction. Its radius has a quadratic relation with respect to the volume of the injection chamber. Therefore, the volume is changing quadratically, which produces a change of injection velocity over the injection length. As a result, the porous wall is creating multiple injection velocities along its length. Instead of modifying the radius as a root function over its length, it was chosen not to modify the injection chamber itself. To solve this problem the porous wall is removed from the injection section and a closed Poly Vinyl Chloride (PVC) cylinder is created and installed, which contains a local slid at the very back of the injection chamber. At this location also the vortex generator is located, as indicated in figure 3.4. The slid and the flange of the vortex generator span over the total circumferential direction of the cylinder as is displayed in figure A.6. Circumferential and homogeneous injection of the fluid in radial direction toward the center of the pipe is thereby promoted. Moreover, the multiplicity of injection velocities over the injection length is reduced and thereby its control improved.

To ensure that disturbances to the smallest scales stay to a minimum, when there is no injection taking place, the maximum width of the slid is calculated to be 10 wall units ($y^+$ units). The $y^+$ unit that is used for this purpose is calculated at $Re = 35000$, largest Reynolds number for which experiments are conducted. This gives the critical width value to minimise the influence on the smallest scales. First the definitions for the wall unit, wall shear velocity...
3.2 Ink visualisation

and the wall shear stress \( y^+ \), \( u_\tau \) and \( \tau_{\text{wall}} \) respectively are defined. Here \( y \), \( \nu \) and \( \rho \) are the distance to the wall, kinematic viscosity and the density of water and \( \frac{\partial p}{\partial x} \) and \( D_{\text{inn}} \) the pressure gradient and the inner pipe diameter respectively.

\[
y^+ = \frac{u_\tau y}{\nu} \tag{3.2}
\]

\[
u = \sqrt{\frac{\tau_{\text{wall}}}{\rho}} \tag{3.3}
\]

\[	au_{\text{wall}} = \frac{\partial p}{\partial x} \frac{D_{\text{inn}}}{4} \tag{3.4}
\]

Combining these equations gives an expression for the distance of one \( y^+ \) unit expressed in wall distance \( y \).

\[
y = \frac{\nu}{\sqrt{\frac{\partial p}{\partial x}} \frac{D_{\text{inn}}}{4}} = 1.004 \cdot 10^{-6} \approx 5 \cdot 10^{-5} \text{ m} = 0.05 \text{ mm} \tag{3.5}
\]

The length of a small scale structures is at least several times the size of one wall unit and is referred to as the Kolmogorov length \( \eta = \left( \frac{\nu^3}{\epsilon} \right)^{1/4} \). Therefore, 10 \( y^+ \) units is chosen as the maximum width over which the injection takes place. This width is referred to as \( d \) and is equal to 0.5 mm. It is assumed to be small enough to avoid changes to the regular shape of the flow structures. For \( R_e = 15000 \) the pressure gradient equals 8.73 kg/m²s², in that case one \( y^+ \) unit is increased to 0.1 mm. The pressure gradient of Reynolds numbers 15000 and 35000 is measured over a pipe length of 2 meters during the construction of the Moody diagram.

A vortex generator is present consisting of a flange, which is formed all around the inner pipe diameter to trip the fluid just before it is entering the pipe.
22 Methods

(a) Side view of the injection mechanism created by C. van Doorne\textsuperscript{18} and the newly installed vortex generator created by C. M. Sanders.

(b) Cross section of the injection mechanism.

Figure 3.4: Parts of the injection mechanism: 1 centering ring, 2 Oring, 3 pipe section, 4 D-ring, 5 hose connecting to pistons, 6 hose-connector, 7 shroud, 8 injection chamber, 9 the new vortex generator which is replacing the old porous tube that was used by C. van Doorne, 10 arrows indicating the injection fluid direction, 11 partition plate.

This favours roll up during the injection, as indicated in figure 3.4, where the water that is used for the injection follows the path indicated by the vectors in blue. The water that is supplied for the injection is first guided along the pipe before it can enter the pipe. Furthermore, the injection chamber is converging. As a result, the shape of the injection chamber is optimally utilized to develop homogeneous flow at the point of injection. Since the effective diameter and the injection width are known to be $D_{\text{eff}} = 0.0339$ m and $d_{\text{inj}} = 0.0005$ m, the injection velocity $u_{\text{inj}}$ and the piston speed $u_{\text{piston}}$ can be derived by making use of the conservation of mass, (equation (3.6)). Rearrangement of the parameters to express them into a function for $u_{\text{piston}}$ gives equation (3.7).

$$\rho A_{\text{pist}} \cdot u_{\text{piston}} = \rho A_{\text{inj}} \cdot u_{\text{inj}} \Rightarrow \frac{\pi}{4} D_{\text{eff}}^2 u_{\text{piston}} = \pi D d_{\text{inj}} \cdot u_{\text{inj}}$$  \hspace{1cm} (3.6)

$$u_{\text{piston}} = \frac{4D d_{\text{inj}}}{D_{\text{eff}}^2} u_{\text{inj}}$$  \hspace{1cm} (3.7)

Where $D = 0.04$ m is the inner diameter of the pipe where the fluid is injected and $\rho A_{\text{pist}} \cdot u_{\text{piston}}$ and $\rho A_{\text{inj}} \cdot u_{\text{inj}}$ are the mass fluxes out of the pistons and at the injection opening respectively. Substituting the dimensions of the present set-up into equation (3.7) gives the relation:

$$u_{\text{piston}} = 0.07 \ u_{\text{inj}}$$  \hspace{1cm} (3.8)

This relation is used to determine the required piston velocity to obtain the desired injection velocity. Injection is done in radial direction with respect to the pipe. The general shape of the injection velocity over time is predetermined in Labview and displayed in figure 6.4 in chapter 6. The same saw-tooth shape is used in all experiments. In the script the parameters displayed in table 3.1 are adjustable.
### Table 3.1: Labview Injection parameters

<table>
<thead>
<tr>
<th>Entry</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_{piston}$</td>
<td>Piston speed</td>
<td>mm/s</td>
</tr>
<tr>
<td>$T_{act}$</td>
<td>Duration of one injection</td>
<td>s</td>
</tr>
<tr>
<td>$T_{wait}$</td>
<td>Time between injections</td>
<td>s</td>
</tr>
<tr>
<td>$nrperiods$</td>
<td>Number of periods</td>
<td>-</td>
</tr>
</tbody>
</table>

#### 3.2.4 The Moody diagram

A Moody diagram is displayed in figure 3.6(a). Along its vertical axis on the right side, the relative roughness is indicated as $\epsilon/d$ which is the roughness height of an obstruction on the wall, divided by the diameter of the pipe. This parameter is mostly known by knowing the material of the pipe and is often known by the producer of the pipe. Furthermore, the horizontal axis indicates the Reynolds number under which the pressure measurements are conducted. This value is also known and can be controlled by controlling the velocity of the flow in the pipe. When the pressure-drop is measured over a unit pipe length the friction factor can be determined per Reynolds number. This will create the horizontally curved lines in the Moody diagram. The overlap with a specific line that is coupled to its relative pipe roughness gives an indication of the normality of the characteristics of the pipe. The configuration of the pressure membrane and the pipe, that is used during the pressure measurements, is displayed in figure 3.2.4. During the pressure measurements transversal waves are present. Due to the velocity that has to be increased over the total 28 meter long pipe this effect has to be taken into account. Therefore, two minutes are taken for each measurement to get a more constant velocity over time. The check valves to the outer most right and left are there to ensure that the membrane is protected from extreme pressure differences during the increase of the flow-rate trough the pipe toward the desired value. The Moody diagram points are measured at Reynolds numbers varying from 15000 to 55000. The range of the friction factor $f$ is varying from 0.02 to 0.03. The results are set out in a log-log plot displayed in figure 3.6(b). Figure 3.6(a) displays the Moody diagram, which is used as as a reference, a fair overlap is present for the area of interest. The temperature during the measurements was kept at a
constant $T = 21.8^\circ$C at this temperature the value of $\nu = 1.004 \cdot 10^{-6} \text{ m}^2/\text{s}$, which is used to calculate the Reynolds numbers. The calibration formula for the pressure transducer that is used during the experiments to measure the pressure difference, $dP$, is given by

$$dP = -0.0242V^3 + 0.5612V^2 + 5.5744V + 0.1204 \quad (3.9)$$

where $V$ is the voltage output from the pressure transducer. After the pressure difference measurements are done over a length of 2 meters, they are substituted into the Darcy friction factor formula.

$$f_D = \frac{2D}{\rho U_b^2 l} \Delta P \quad (3.10)$$
3.2 Ink visualisation

(a) Indication of the region of interest (green) in the Moody diagram.

(b) Log-log plot of the measurement points (blue) and their 5th Colebrook-White iteration (green).

Figure 3.6: Moody diagram comparison.
To create a more accurate result, an iteration process is done using the Colebrook-White equation for turbulent regimes in circular pipes.

\[
\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{\varepsilon}{3.7D_h} + \frac{2.51}{Re\sqrt{f}}\right)
\]  

(3.11)

Here, the hydraulic diameter \(D_h\) equals the inner diameter of the pipe. Furthermore \(\varepsilon\) is defined as the surface roughness of the pipe inner wall. After the fifth iteration, the friction factor converged. For the derivation of the Darcy friction factor a quick review is offered in Appendix C.3. The following results were obtained considering a relative pipe roughness \(\frac{\varepsilon}{D} = \frac{0.0025}{40} = 6.25 \cdot 10^{-5}\). The results, in figure 3.6, show a fair overlap within the region of interest. It is an indication for good flow conditions inside the pipe.

In the laminar regime a different approach is used to obtain the pressure difference. For laminar flow in a circular pipe the following relation is used.

\[
\frac{f}{Re} = \frac{64}{300} \approx 0.2133
\]

(3.12)

This value is substituted into Darcy’s expression for the friction factor and rearranged for the pressure.

\[
\Delta P = \frac{fDV^2\rho}{D} = \frac{0.2133(0.00753)^21000}{0.04} \approx 0.3 N/m^2
\]

(3.13)

Thereafter this value is substituted into equation (3.5) to get the length of one wall unit, which gives that \(y = \frac{\nu}{\frac{\partial P}{\partial x}} = \frac{1.004 \cdot 10^{-6}}{0.3 \frac{0.04}{4000}} \approx 5.8 \cdot 10^{-4} m = 0.58 \text{ mm}\), since the smallest structures are a multiple of this value the injection slit is thin enough not to disturb these structures before injection.

### 3.2.5 Injection principle considering the interaction between small and large scales

This specific way of injecting is chosen, based on the idea that a ring vortex is creating its own forward propelling velocity. Thereby it is assumed that the vortex generator will initiate a core circulation (\(\Gamma_0\)). The self propelling velocity of a viscous vortex ring with respect to time is defined by equation (2.46). There is a considerable difference in downstream velocity of the small scales in the pipe with respect to the injected large scale vortex. The small scales that interact at the injection location during injection convect downstream slower than the vortex ring. It propels itself downstream by its self induced trust. Therefore, it has the opportunity to interact with the undisturbed small scales that are located at the measurement section.
3.2 Ink visualisation

3.2.6 Forming the vortex and ensuring a homogeneous injection

The injection is performed in such a way that the injected velocity will rapidly increase after which it is gradually decreasing over time. This is done to prevent a rapid recovery of the velocity profile closer to the wall. In this way roll-up of the vortex is further enhanced as explained in section 2.3.2. The injection will furthermore act as a natural diaphragm of water that protects the generating vortex from the upstream velocity.

Rayleigh’s 1D inflection point criterion is used that states that there should be at least one inflection point to make $U(z)$ unstable. Furthermore, it indicates that an inflection point in $U_z$, correspond to a maximum in the amplitude of the vorticity, since $\Omega(z) = -\frac{\partial U}{\partial z}$. The idea is to generate this effect in radial direction due to a circumferential injection towards the center of the pipe.

![Inflection point](image)

**Figure 3.7:** Rayleigh’s inflection point criterion in 1D becomes a 2D ring for the generation of 3D ring vortices.

During the visualisations a white background is placed behind the test section to increase the contrast. Furthermore a spotlight is placed above the pipe section where the camera is recording these amazing structures, which will be further elaborated in chapter 6. Photos that are taken from the coherent structures are included to that section.

The first experiments are done to show whether a vortex will form and if it will be a coherent structure. In order to quickly modify the vortex generator in the mechanism it is installed between the two manually operating valves.

To ensure a homogeneous injection, a proper venting system is made. Furthermore, the supply tubes are transparent such that trapped air can be detected. This can also be checked due to the transparency of the injection chamber. Furthermore, an effort is taken to seal the system to prevent air from entering the injection chamber. After the visualisation experiment has been conducted the injection mechanism is reinstalled upstream of the SPIV test section. Since the feeding of ink into the injection chamber is done in a symmetric manner only one half of the system is explained. The injection system is fed through the hose, indicated by number 1 in figure 3.8. As the ink is flowing through the hoses it arrives at locations 2, 3, 4, 5 and 6. From splitters 3, 4 and 5 the ink is injected into the injection chamber via the ports 7, 8 and 9 respectively. Splitter 2 and 6 are connecting the two symmetric sides of the injection system on the lower and upper side respectively. Venting is done with an injection
cylinder to absorb the trapped air and part of the fluid. With a clip (11) the venting-hose is sealed.

![Image showing side and top views of system components.](image)

(a) Side view.  
(b) Top view.

**Figure 3.8:** System of the water supply to the injection chamber and the venting system.

### 3.2.7 Determining the injection velocity using Saffman’s propagation equation

The circulation $\Gamma(r,t)$ at any location can be determined by means of integration over the volume, that contains the vortex, in the known 3D velocity field. The time and velocity $U$ at any location is known and the vortex radius $R$ can be obtained using equation (3.14).

$$R = R_{pipe} - r_c$$  \hspace{1cm} (3.14)

where $r_c$ is the core radius of the vortex which can be measured. The distribution of circulation corresponding to the Oseen-Lamb viscous filament is used and is stated here as equation (3.15)$^{17}$.

$$\Gamma(r,t) = \Gamma_0(1 - e^{-r_c^2/4\nu t})$$  \hspace{1cm} (3.15)

The radius of a vortex core, $r_c$, is a parameter that is directly coupled to the shape and strength of a coherent structure. The Taylor hypothesis indicates that these structures should keep their coherency at least for multiple pipe diameters downstream. This hypothesis is applied throughout this work. Therefore it is assumed that $r_c$ is constant during the measurement. The radius of the vortex ring, $R$, in equation (3.14) is also assumed constant during the measurement. Note also that this parameter is bounded by the radius of the pipe. Furthermore, the circulation $\Gamma$ is assumed constant over the time of the measurement. It is assumed that the vortex generation time ($t_{vort.gen}$) is relatively short in such a way that $t_{vort.gen} \ll t_1 - t_0$. In this way the injection velocity can be calculated by substituting the time $t_{vort.arr}$ that has been determined in section 2.4 into the equation for the injection velocity.
3.2 Ink visualisation

$u_{inj}$, equation (3.16). Using that $r_c < R = 0.02 \text{ m}$ and assuming a self-propulsion of the generated vortex of 3 times the bulk velocity the maximum vortex arrival time at $Re = 300$ is determined by equation 3.17.

$$u_{inj} = \frac{\Gamma}{4\pi R} \left[ \log \frac{8R}{\sqrt{4\nu t_{\text{vort.arr.}}}} - 0.558 \right]$$  \hspace{1cm} (3.16)

$$t_{\text{vort.arr.max}} = \frac{x}{3U_b} = \frac{0.45}{3 \cdot 0.00753} = 21.4 \text{ s}$$  \hspace{1cm} (3.17)

The estimated vortex propagation velocity of $3U_b$, that is based on the mirrored vortex and the injection velocity that super-positioned on the bulk velocity seems reasonable. The generated structure is indeed captured and displayed in figure 6.7, during a measurement conducted 10-25 seconds after its injection.

Taking the $r_c$ in equation (3.15) in the order of the pipe radius which can be verified from figure 6.9 section 6.1, for this laminar flow and the kinematic viscosity of water at room temperature $\nu = 1.004 \cdot 10^{-6}$ the e-power in equation (3.15) can be determined to be

$$e^{-\frac{r_c^2}{4\nu t_{\text{vort.arr.max}}}} = e^{-\frac{0.02^2}{4 \cdot 1.004 \cdot 10^{-6} \cdot 21.4}} \approx e^{-4.66} \approx 0.0095$$  \hspace{1cm} (3.18)

Therefore, the reduction of $\Gamma$ is less than 1%, which means the e-power $\approx 0$ and the Taylor "frozen turbulence" assumptions are indeed applicable, and $\Gamma$ can be taken constant. Note that the vortex-core radius at $Re = 15000$ is of the order of $1/5R = 4 \cdot 10^{-3}$. This is observed during the ink visualisation displayed in figure 6.2 section 6.1.2. Therefore the e-power of equation (3.15) during measurements at $Re = 15000$ is determined in equation (3.19).

$$e^{-\frac{r_c^2}{4\nu t}} \approx e^{-\frac{0.004^2}{4 \cdot 1.004 \cdot 10^{-6} \cdot 0.3}} \approx e^{-10} \approx 4.5 \cdot 10^{-5}$$  \hspace{1cm} (3.19)

This result shows that although the generated vortex-core radius is decreasing at higher Reynolds numbers the Taylor hypothesis holds increasingly better due to the decrease in vortex arrival time. Therefore, the assumption, that $\Gamma$ in equation (2.46) is constant, is appropriate.
Chapter 4

Stereoscopic Particle Image Velocimetry

In this chapter the details of the SPIV set-up are discussed. First however, a small overview of the working principle of SPIV is provided. During a SPIV measurement, 10µm diameter hollow spherical cells are added to the water volume. These particles will be illuminated by a laser plane that is positioned perpendicular with respect to the longitudinal direction of the pipe. The laser-plane is activated under a set frequency which is depending on the bulk velocity that is used during the measurement. These values are displayed in table 5.1, chapter 5. Therefore, the time between two measured planes is known. From the displacement of the tracer particles between two subsequent recordings the 3D velocities is deduced. After this process, the rotation of the field can be determined. Thereafter, the iso-$Q$ and iso-$R$ values of each plane can be connected to form the 3D structures of the flow.

4.1 Positioning the high speed resolution cameras

4.1.1 The HSR cameras

Two high speed, high resolution(HSR) VC-Imager Pro HS 4M cameras are used, which have 2k x 2k pixels and a 18GB storage capacity. They both have a CMOS sensor. The measurements are done at a 200, 1279 and 640 Hz recording rate. This resulted in a measurement time of 15, 2 and 2.5 seconds at a Reynolds number of 300, 15000 and 35000 respectively. The image magnification factor $M_0$ is defined as the ratio between the sensor size $d_i$ with respect to the object size $d_o$, which is measured by making use of the calibration grid that is placed inside the test section (that is inside the pipe which is filled with water). It is obtained by the distance between 18 calibration marks around the center of the sensor and dividing it by the physical distance between the same marks on the calibration plate.

$$M_0 = \frac{d_i}{d_o} = \frac{|340 - 1712|11\mu m}{18 \cdot 2 mm} = 0.42$$ (4.1)


(a) Top view of the configuration of the test section with the two cameras, mirror, lenses and more which is explained in Appendix A.

(b) One side of the symmetric camera setup.

Figure 4.1: Setup of both HSR cameras and their Scheimpflug angle.

4.1.2 Determining the Scheimpflug angle

The magnification factor is now used to determine the angles of the camera and Scheimpflug adapters in order to compensate for the oblique viewing angle and camera lenses. First the aperture is closed so that the focal depth is minimised. This creates an intersection between the object plane and the lens plane for which the image is sharp. When the cameras and the Scheimpflugs are positioned correctly, the object plane, lens plane and image plane intersect in one point. In theory, when this is realised, all of the image should be in focus. However, in practice, the image that is created will contain only a centred area around the midpoint of the calibration plane that is in focus. Therefore, the aperture is opened further so that the focal depth increases and the area on the calibration grid will be in focus in such way that it overlaps the region of interest. The set-up of the cameras top view is given in figure 4.1. The camera axis and the Scheimpflug axis are perpendicular to the image plane and lens plane, also the angle $\theta = 45^\circ$. The Scheimpflug angle ($\alpha$) can be determined by making use of the relation between the angle of the object plane and the image plane. This relation is known as the Scheimpflug condition \(^{23}\):

\[
M_0 = \frac{\tan \alpha}{\tan \theta} \Rightarrow \alpha = \arctan (0.42) \approx 23^\circ
\] (4.2)

Here, $\theta$ is defined as the angle between the lens plane and the object plane and $\alpha$ as the angle between the lens plane and the image plane\(^{24}\). Furthermore, from figure 4.1(b) the camera angle can be determined as: $\gamma = \theta - \alpha = 45^\circ - 23^\circ = 22^\circ$. All angles for the
set-up are now determined. It is assumed that the lens of a camera is a thin line while in reality it consists of a series of lenses. Therefore, it is checked if the image is falling outside the sensor area when the Scheimpflug is put under an angle of 23°. Attaching a target onto the lens that moves with the Scheimpflug angle does not result into a shift of the image projection on the sensor. Therefore, the assumed location of the axis of rotation is correct.

### 4.1.3 Calculating the light sheet thickness

To determine the light sheet thickness it has to be taken into account that the optical axis is under an angle of \( \theta = 45^\circ \) with respect to the light sheet. Allowing 8 pixels of particle displacement seen by the camera means an absolute out-of-plane displacement \( |\Delta z| = 8/0.42 \cdot \sqrt{2} \cdot 11 \mu m \approx 0.3 \text{ mm} \). The light sheet thickness is defined as:

\[
\Delta z_0 = 4|\Delta z| = 1.2 \text{ mm}
\]

This is the minimum value of the thickness of the light sheet so that a particle displacement of 8 pixels can be detected with ease\(^{24}\). In practice the light sheet thickness will vary from side to side over the span of the cross-section. Therefore, this variation is calculated in section 4.2.1.

### 4.2 Optical systems, calibration procedure and the resolution

Since the light has to pass through different kind of media it will deform where the positions of the calibration grid points are. Therefore, prior to a set of measurements a calibration needs to be performed. A software is used that will both detect markers, and puts a polynomial fit through them to de-wrap the image of the cameras into the known Cartesian coordinate configuration. This section discusses how the calibration grid is installed and how it can be adjusted for a correct calibration procedure. Moreover, it describes how the laser-plane thickness determines how large the displacements of the calibration glass can be during the calibration process and how it is coupled to the resolution of the measurements.

#### 4.2.1 Positioning the laser, lenses and mirror

By letting the laser pass through a concave cylindrical lens the height of the laser plane is formed. Then the spherical lens forms the thickness of the plane, which is mirrored to illuminate the pipe perpendicularly. The radius of the spot size \( d/2 = 2.5 \text{ mm} \) as it impinges on the cylindrical lens with focal point \( f_{cyl} = -25 \text{ mm} \). Since the desired height is known to be \( h/2 = 20 \text{ mm} \), the distance between the two lenses \( \Delta x_{rel} \) can now be computed by making
use of goniometric rules.

\[
d/2 = \frac{h/2}{|f_{cyl}|} \Rightarrow \Delta x_{rel} = \frac{f_{cyl}(h - d)}{d}
\]  

(4.4)

When \(\Delta x_{rel} = 175 \text{ mm}\) this will result in a laser plane height \(h = 40 \text{ mm}\). Since the cylindrical lens is only spreading in vertical direction its thickness in horizontal direction remains the same at the moment it reaches the spherical lens. This lens has a focal point \(f_{sph} = 400 \text{ mm}\). Since the laser behaves as a Gaussian beam, its waist thickness develops non-linear near its minimum. To determine if linearisation of the development of the width of the plane can be applied the Rayleigh length has to be obtained. Therefore, the angle \(\theta\) needs to be calculated which is defined in \text{rad}\ and is equal to \(\Theta/2\) in figure 4.2. The focal length of the spherical lens equals \(f_{sph} = 400 \text{ mm}\). The angle \(\theta = \arctan\left(\frac{d/2}{f_{sph}}\right) \approx 0.00625 \text{ rad}\). The wavelength of the laser \(\lambda = 527 \text{ nm}\). Therefore, the minimum waist can be determined with equation (4.5).

\[
w_0 = \frac{\lambda}{\pi\theta} = 2.68 \cdot 10^{-5} \text{ m}
\]  

(4.5)

Therefore, the Rayleigh length is determined by using equation (4.6).

\[
z_R = \frac{\pi w_0^2}{\lambda} = 0.0043 \text{ m}
\]  

(4.6)

To set the distance between the waist and the glass surrounding the test section, the distance between the spherical lens and the mirror can be varied. In this case it is set to 96 mm. Since the distance between the waist and the glass that surrounds the test section is 46 mm. This distance is 10.69 times the Rayleigh length. This makes linearisation possible to determine the width of the laser plane at the glass. Furthermore, the light will travel through multiple mediums, adding differently to the thickness of the plane. Using the Snellius equation the new angle can be obtained as:

\[
\frac{\sin(\theta_i)}{\sin(\theta_{i+1})} = \frac{n_{i+1}}{n_i} \Rightarrow \theta_{i+1} = \arcsin(\sin(\theta_i)\frac{n_i}{n_{i+1}}))
\]  

(4.7)

\[\begin{array}{c}
\text{Figure 4.2: Graphical representation of laser beam waist}
\end{array}\]
4.2 Optical systems, calibration procedure and the resolution

The angle at which the plan impinges on the glass rectangle equals $\theta_1 = \arctan(0.29/25) = 0.36^\circ$

With the calculated new angles and the measured distance over which the light travels, the added thickness of the laser plane can be determined. Table 4.1 summarises the added thickness to the laser plane during its travel through the test section onto the backside of the pipe.

The laser plane thickness is approximately 1 mm at the beginning of the pipe and ends with a thickness of 1.4 mm at the backside of the pipe which gives $(\Delta z_0)_{\text{eff}} \approx 1.2$ mm, which means that where the laser-plane enters the pipe, the detection of the out-of-plane motion of 8 pixels in length is less accurate than that at the location where the laser plane leaves the pipe. However, this detection in practice was performed without difficulty. Therefore, an other design rule for the thickness of the laser plane is ensured over the entire measurement.
### Table 4.1: Laser plane thickness variation, only one half of the beam width

<table>
<thead>
<tr>
<th>i</th>
<th>$\theta_i$ [deg]</th>
<th>medium</th>
<th>$n_i$</th>
<th>$\Delta x_i$ [mm]</th>
<th>$\Delta (d/2)_i$ [mm]</th>
<th>Front [mm]</th>
<th>Back [mm]</th>
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<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>0.24</td>
<td>Glass</td>
<td>1.5</td>
<td>3</td>
<td>0.0126</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
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<td>0.27</td>
<td>Water</td>
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<td>40</td>
<td>0.1885</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
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<td>0.24</td>
<td>Glass</td>
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<td>0.0067</td>
<td>0.4978</td>
<td>-</td>
</tr>
<tr>
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<td>40</td>
<td>0.1885</td>
<td>-</td>
<td>0.6863</td>
</tr>
</tbody>
</table>

section, which is described in the following section, that discusses the focal depth of the field known as $\delta z$.

### 4.2.2 Relation between the light sheet thickness and particle concentration

Illumination of the particles is done by a dual-cavity, Nd:YLF laser. It has a wavelength of $\lambda = 527$ nm with output energy up to 30 mJ per pulse per laser head at a repetition rate of 1000 [Hz] and a frequency range between 0-10 kHz. It is operated at 60% of its optimal output energy to optimise the dynamic range of the cameras, in such a way that each pixel is not under, or over, lighted. The laser beam diameter is approximately 5 mm. The cameras are focused with an $f^\# = 11$, so that the depth of field $\delta z$ can be determined as:

$$\delta z \approx 4\lambda \cdot f^2 \left( \frac{1}{M^2_0} + 1 \right) = 1.7 \text{ mm} \quad (4.8)$$

Since $\Delta z_0 \approx 1.7$, $\delta z > \Delta z_0$. Therefore, all particles that are captured within the laser plane, will be in an in-focus plane. These now known parameters can be used to check for peak locking. But before that a selection has to be made of which tracer particle is going to be used. The Potter industries, hollow, 110P8 Sphericel are chosen as the SPIV tracer particles. These particles have a high refractive index, have a relatively low price and are relatively close to being neutrally buoyant. The tracer concentration of these particles equals $1.10 \pm 0.05 \cdot 10^6$ g/m$^3$ and the finite diameter of the particles $d_p = 10 \mu m$. The particle image diameter can be calculated as:

$$d_r \approx (M_0^2 d_p^2 + d_s^2 + d_a^2)^{1/2} \quad (4.9)$$

With $d_s$ as as the diffraction-limited spot diameter being larger than the diameter of the aberrated image of a point source $d_a$ and larger than the magnified particle diameter $M_0 d_p$, the image is dominated by the diffraction. Therefore, the particle image diameter is calculated as:

$$d_r \approx (M_0^2 d_p^2 + [2.44(1 + M_0) f^\# \lambda]^2)^{1/2} \Rightarrow d_r \approx 21 \mu m \quad (4.10)$$
4.2 Optical systems, calibration procedure and the resolution

This means that the amount of pixels to indicate a particle will be $21/11 = 2$. In practice 3 pixels also occurred, which indicates that peak locking is unlikely to occur since this value is empirically set to avoid peak locking. According to Einstein’s formula (Einstein 1906a, 1911; Roscoe 1952) for the viscosity of a dilute suspension of uniform spheres, the added viscosity does not exceed 0.25% of the value without particles when the volume fraction is not allowed to exceed 0.1%\textsuperscript{24}. The water that is used is first deionised before it is put into the system.

The total volume is calculated in Appendix A and equals ($0.6031 + 0.001$) m$^3$ for the first measurement. Taking 0.1% gives 0.0006041 m$^3$. Therefore, the maximum added mass of particles becomes:

$$ (m_{\text{part}})_{\text{max}} = V_{\text{water}} (+0.001[m^3]) \cdot 0.001 \rho_{\text{tr.part}} \tag{4.11} $$

An amount of 0.001 m$^3$ is added to the total volume, because the 100 g particles are first solved in 1000 ml water, before it is add to the system. This gives $(m_{\text{part}})_{\text{max}} = 664.51$ g. To be careful with the adding of particles a start is made to add roughly 1/7 of this amount, 100 g of particles. This provided the desired amount of particles to conduct measurements with. It produced 6 to 8 particles in a 16 x 16 pixels window size. The volume per particle equals:

$$ V_{\text{tr.part}} = \frac{4}{3} \pi (5 \cdot 10^{-6})^3 \text{ m}^3 = 5.24 \cdot 10^{-16} \text{ m}^3 \tag{4.12} $$

The weight per particle equals:

$$ m_{\text{cel}} = V_{\text{tr.part}} \rho_{\text{tr.part}} = 5.24 \cdot 10^{-16} \cdot 1.1 \cdot 10^6 \text{ g} \approx 5.7 \cdot 10^{-10} \text{ g} \tag{4.13} $$

This means, that the amount of particles added equals:

$$ \frac{100 \text{ g}}{5.7 \cdot 10^{-10} \text{ g/part}} = 1.75 \cdot 10^{11} \text{ tracer particles.} \tag{4.14} $$

Divided over the total volume, the tracer concentration will become equal to:

$$ C = \frac{1.75 \cdot 10^{11}}{0.6041} \text{ part/m}^3 \tag{4.15} $$

The source density is defined as:

$$ N_s = \frac{C \Delta z_0}{M_0^2} \frac{\pi}{4} d_r^2 \tag{4.16} $$

Where $C$, $\Delta z_0$, $M_0$, and $d_r$ are defined as the tracer concentration, light-sheet thickness, image magnification and the particle image diameter. It indicates whether the condition of an image consisting of individual particles is fulfilled ($N_s \ll 1$). To be certain that this criterion is met, its value is calculated for the amount of particles that are used as a starting quantity.

$$ N_s = \frac{2.9 \cdot 10^{11} 12 \cdot 10^{-4}}{0.42^2} \frac{\pi}{4} (10 \cdot 10^{-6})^2 = 0.15 \text{ part/m}^2 \ll 1 \tag{4.17} $$

The image density $N_I$ can be calculated by using the interrogation area $A_I$.

$$ N_I = \frac{C \Delta z_0}{M_0^2} A_I \tag{4.18} $$
Or:

\[
N_I = \left( \frac{4A_I}{\pi d_s^2} \right) N_S = \frac{4(16 \cdot 11 \cdot 10^{-6})^2}{\pi \cdot 10 \cdot 10^{-6}} 0.15 \approx 60
\] (4.19)

However, after addition of the particles into the system typically 8 to 13 particles are found inside an interrogation window. This means that the effective concentration \(C_{eff}\) is lower by a factor of 2 and \(\langle N_S \rangle_{eff} = 0.075 \text{ part/m}^2\). This can be explained by the fact that particles can stick to the wall of the pipes in the system. Furthermore, the linear dimension of the interrogation area \(D_I\) is chosen to be 32 pixels. In addition, the absolute displacement vector in the image domain \(|\Delta X|\) is between 6 and 8 pixels. The image density is kept higher than 1 and about 10 on purpose, since it is one of the design rules determined by means of the Monte Carlo method\(^{26}\) and also referred to in the book of "Particle Image Velocimetry"\(^{24}\). In total this means that the following design parameters are met:

\[N_I > 10, \quad |\Delta X| < \frac{1}{4} D_I, \quad |\Delta z| < \frac{1}{4} \Delta z_0\]

### 4.2.3 Calibration procedure and positioning the calibration grid

To position the calibration grid, it is attached to an RVS holder which on its turn is attached to the assembled 3D transverse as displayed in section A.1, figure A.1(a). Before inserting the calibration grid inside the pipe, the pipe sections indicated by number 8 is removed as a whole. Furthermore, the insertion tank, indicated by number 10, has to be refilled with water. With a piece of white cloth, attached to a flexible rod, the inner part of the pipe in test section is cleaned. This is done to remove particles that stick to the wall after some time. Thereafter, the grid on the holder is inserted and attached to the micro transverses. Indicated by the numbers 1, 2 and 3 in figure A.1(a), the target can be translated along 3 axis by using three micro transverses. This can also be done more roughly in the up-stream direction by the rail onto which it is attached indicated by number 9. The rail has 8 contact points on top of the insertion tank that can be adjusted. These are indicated by numbers 1-4 in figure A.1(b). In this way a parallel alignment with the direction of the pipe can be realised. The calibration glass consists of a Cartesian grid.

The calibration targets span the entire cross-section and are spaced 2 mm with respect to each other. They are displayed in figure A.4(a). More details about the properties and size of these products can be found in chapter A. The calibration target is first put parallel to the laser plane. For safety reasons this plane will be operating under a lower power. The mirror is adjusted to create a parallel plane with respect to the inserted calibration grid. The orientation of the grid is perpendicularly with respect to the longitudinal direction of the pipe. Thereafter, a three plane, calibration is conducted. Therefore, the calibration plane is traversed three times. Each time over a distance that is approximately equal to half of the mean light sheet thickness (\(\approx 1.2 \text{ mm}\)). The targets will be reflecting the light with respect to their dark background. How they are recognised is displayed in figure A.4(b). Since the light has to pass different kind of media it will deform where the positions of the calibration grid points are. However, the software that is used will not only detect the markers but will also make a polynomial fit trough these points to de-wrap the image of the cameras into the known Cartesian coordinate configuration.
### Table 4.2: Experimental parameters $Re = 300$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe diameter</td>
<td>40 mm</td>
</tr>
<tr>
<td>- length</td>
<td>28 m</td>
</tr>
<tr>
<td>- material</td>
<td>Glass</td>
</tr>
<tr>
<td>- wall thickness</td>
<td>1.6 mm</td>
</tr>
<tr>
<td>Flow fluid</td>
<td>Water</td>
</tr>
<tr>
<td>- $Re$</td>
<td>300</td>
</tr>
<tr>
<td>Seeding type</td>
<td>Sphericel</td>
</tr>
<tr>
<td>- diameter</td>
<td>10 $\mu$m</td>
</tr>
<tr>
<td>Laser sheet</td>
<td>dual-cavity, Nd:YLF</td>
</tr>
<tr>
<td>- maximum energy</td>
<td>30 mJ/pulse</td>
</tr>
<tr>
<td>- wave length</td>
<td>527 nm</td>
</tr>
<tr>
<td>- pulse duration</td>
<td>0.005 s</td>
</tr>
<tr>
<td>- thickness</td>
<td>1.2 mm</td>
</tr>
<tr>
<td>Camera type</td>
<td>VC-Imager Pro HS 4M</td>
</tr>
<tr>
<td>- resolution</td>
<td>2k x 2k px</td>
</tr>
<tr>
<td>- discretization</td>
<td>12 Bit $(2^{12} = 4096)$</td>
</tr>
<tr>
<td>- repetition rate</td>
<td>200 Hz</td>
</tr>
<tr>
<td>- lens focal length</td>
<td>105 mm</td>
</tr>
<tr>
<td>Imaging f-number</td>
<td>11</td>
</tr>
<tr>
<td>- viewing angles</td>
<td>$\pm$45 degrees</td>
</tr>
<tr>
<td>- image magnification</td>
<td>0.42</td>
</tr>
<tr>
<td>- viewing area</td>
<td>40 x 40 mm$^2$</td>
</tr>
<tr>
<td>- exposure delay time</td>
<td>1.5 ms</td>
</tr>
<tr>
<td>- maximal particle displacement</td>
<td>8 px</td>
</tr>
<tr>
<td>PIV analysis reconstruction method</td>
<td>3D calibration $(Soloff et all.)$</td>
</tr>
<tr>
<td>- interrogation area</td>
<td>32 x 32 px</td>
</tr>
<tr>
<td>- Overlap interrogation area</td>
<td>75 %</td>
</tr>
<tr>
<td>- approximate resolution</td>
<td>0.2 x 0.3 mm$^2$</td>
</tr>
</tbody>
</table>
5.1 Velocity Profiles

5.1.1 The theoretical velocity profiles

The first set of measurements is carried out at $Re = 300$, for which the centreline velocity is approximately $17 \text{ mm/s}$. At this Reynolds number, the flow velocity should be mostly parallel to the axis of the pipe. For laminar pipe flow the velocity profile is constant in time. The characteristic velocity profile in a pipe with laminar flow is called the Hagen-Poiseuille profile, which is an axis symmetric parabolic profile, as indicated in figure 5.1. The velocity in the pipe is gradually decreasing when the wall is approached where the no slip condition holds. In the turbulent regime, the velocity is constantly changing and the mean flow no longer yields a parabolic velocity profile. However, the time averaged velocity profile results in the shape of a truncated parabolic profile. This profile has a large velocity gradient close to the wall as indicated in figure 5.2. Fully developed turbulent pipe flow is statistically stationary and homogeneous in the $z$ and $\theta$ directions, which is explained in section ??.

Consequently, the mean velocity only varies with the radius. However, the large variety of turbulent structures perfectly transport momentum. This transport is done rather rapidly between different velocity layers. Therefore its mean velocity profile becomes more flat in the core of the pipe.

Figure 5.1: The axis symmetric laminar Hagen-Poiseuille velocity profile showing an axis symmetric profile
5.1.2 The Coriolis effect

The laminar velocity profile as displayed in figure 5.1 is rather difficult to maintain at very low Reynolds numbers in long pipes since disturbances could build up along the length of the pipe. One of the main causes that deviates the profile from its axis of symmetry is the Coriolis force which is created by the rotation of the earth. The deviation is increasing with an increasing Reynolds number\(^{19}\). The set-up has been moved in the past from a north-south orientation to an east-west orientation. This increased the inner product between the rotational axis of the earth and the pipe axis, resulting in an increase in deviation of the parabolic velocity profile as indicated in figure 5.3.

![Figure 5.3: Deviation of the Hagen-Poiseuelle velocity profile due to the Coriolis effect in laminar pipe flow](image_url)
5.2 Subdivision of flow characteristics

5.2.1 Coherent structures

The word structure is now described in more detail to get a greater understanding of its meaning and a better feeling for the phenomenon of interest. Mainly structures are described as elementary organized fluid motions that are most often called eddies or coherent structures. Another way of defining coherent structures is used by Hussain. He states that a coherent structure is a connected turbulent fluid mass with instantaneously phase-correlated vorticity over its spatial extent. To elaborate on this, motions can be thought of as individual entities only if they persist for long times, which is called temporal coherence. The structures are associated with Reynolds stresses, and transport momentum. Furthermore, these structures are producers and dissipaters of turbulent kinetic energy. Some of the coherent structures in wall bounded turbulence that are widely known are known as canes, hairpin vortices and ring vortices. Their shape, scale range and interaction however largely depend on the Reynolds number. They are both energetic and play a role in the events that are taking place in the flow.

Hairpin vortices

Hairpin vortices are formed by regions of low speed flow due to velocity gradients. They form with respect to their surrounding free-stream.

(a) Theodorsen’s impression of the hairpin vortex in span-wise orientation with respect to the mean flow, showing also its lift and drag. (b) Sublayers of organised hairpin structures in wall turbulence

Figure 5.4: The small-scale participation to the large-scale by the alignment of smaller scale hairpins that induce a larger scale motion in the form of a large-scale structure referred to as a bulge
An impression of the hairpin vortex as it is initially described\(^\text{30}\) is displayed in figure 5.4(a). The inner side of the hairpin contains a velocity fluctuation with an opposite direction with respect to the mean velocity. Turbulent structures are relatively thin and they vary in size\(^\text{32}\). Since inertial forces in turbulent flows are relatively high with respect to viscous forces, smaller structures will have the opportunity to be coherent for a longer time and therefore they are subject to stretching, which increases their strength and gives them the opportunity to grow larger and thinner.

Coherent structures that align closely after each other, will form unified structures referred to as bulges or packets\(^\text{33,36,37}\). These hairpin packets are in turn able to coherently align to form very larger scale motions (VLSMs) or will form sub-layers in which new structures can develop\(^\text{38,29}\). This phenomenon is indicated in figure 5.4(b). During the alignment of the hairpins events occur which are described in section 5.2.2.

**Ring vortices**

The closed ring vortex is often seen when a puff of smoke from a cigar is thrown into the air. It becomes visible since the vortex entrains the smoke inside the ring due to its low pressure. A ring vortex front view and side view is displayed in figure 5.5(a). It is also encountered during various ways of propulsion. A produced vortex ring can be seen as a closed volume of vortical fluid, defined as the vortex atmosphere\(^\text{39}\). This is much like the bubble of opposite oriented fluid in front of the hairpin vortex that opposes its upstream flow. Therefore, the characteristics of a vortex ring are of particular interest in this report. Since the form and characteristics of the hairpin vortex and the closed ring vortex are closely related, the hairpin is assumed that it is a derivative of the ring vortex, and that the ring vortex is the ideal shape to effectively transport a volume of fluid with a velocity that is opposite with respect to its free stream. Closed ring vortices exist for both laminar and turbulent flows as displayed in figure 5.5. Furthermore, figure 5.5(b) is showing a counter rotating ring vortex, in a compressible flow, that is located in front of the ring vortex bubble and is convected over it in downstream direction\(^\text{40}\).

(a) From left to right, the front and side view of a smoother developing laminar vortex ring\(^\text{39}\). The influx on the backside of the vortex bubble is visible. Counter rotating vortex rings appear to be absent, in contrast to the turbulent case, where entrainment rings are visible and are absorbed at its influx. 

(b) Side view, a counter rotating vortex ring travelling over a vortex bubble in a turbulent regime at Mach 1.7\(^\text{40}\).

**Figure 5.5:** Ring vortices in the laminar and turbulent regime, from left to right.
For incompressible flows these counter rotating entrainment vortices also occur and can be detected at a later stage after the ring vortex has been generated. However, the existence of these isolated ring vortices is very hard to measure. The primary difficulties are twofold. First, one has to define the unsteady boundary of the ring vortex. Secondly, a ring vortex needs to be maintained long enough in a test section to conduct the measurements. Nonetheless, these problems have been solved in previous work. This resulted in the detection of the isolated entrainment ring vortices, displayed in figure 5.6. Since these coaxial, smaller scaled, ring vortices are of oppositely signed circulation with respect to the main vortex that they approach, they will grow in radius. Their cores contract in order to preserve volume, and their vorticity increases in order to preserve circulation. Therefore, their presence becomes more apparent as they are stretched by the bubble of the main vortex.

Figure 5.6: Instantaneous streamlines and vorticity patches (3% of the peak vorticity in the vortex core), at time $T=5.74$ s. Minimum vorticity level is $0.3 \text{ s}^{-1}$. for LD2-CF0 protocol at $Re=1400$ based on piston speed and cylinder exit diameter.
5.2.2 Events

During the alignment of the hairpin vortices as described in section 5.2.1 certain events occur. The main events are described as bursts, which propel the low speed fluid into a region of higher momentum. In this thesis the idea is posed that this could be the effect of a breakup of one of the aligned vortices. In that case a sudden increase of circulation is realised. This is due to the fact that part of the upward velocity field generated by the hairpin “head” is counteracted by the downward flow induced by the upstream hairpin head. Break-up of one of the hairpin vortices may be caused by entanglement of two hairpins into each other (as indicated in figure 5.7) during a merging process of hairpins. This could lead to a burst if their direction of vorticity is far from tangential with respect to each other.

An other phenomenon displayed in figure 5.8(a) is the entrainment of smoke on top of bulges, which could not penetrate further down. This indicates that hairpins isolate the area underneath them from the outside flow environment in a certain way as is displayed in figure 5.8(b), where the red color consists of relatively high velocity flow and the blue color low velocity flow. In fact it is very similar to what takes place during an injection in the measurements in this thesis to create a new vortex. This is described in more detail in section 2.3.2. Events like bursts increase the turbulent kinetic energy.
5.3 Detecting the injection

5.3.1 The four phases in a measurement

During the injection with ink four regions are distinguished. These regions are described in more detail in section 6.1.2. The first phase is the moment before injection. The second phase, where the injection is executed and the generated vortex is detected. The third part, where entrainment vortices seem to be present. And the last phase, where the flow is recovered. The phases are clearly present, but they are stretched out in space and time. Therefore the first measurements, at $Re = 300$, are split up into these four parts. Since very low bulk speed is used, it is only possible to capture the change between these four phases if the measurement time will be long enough. Relative long measurements are conducted, which are also partly overlapping each other. This can be realised by lowering the frequency rate of the cameras for these measurements. Table 5.1 gives an overview of the camera frequencies that are used during the experiments. Due to a lower frequency the cameras are capable of storing the information for a longer measurement time. At higher Reynolds numbers all the four stages are contained within one measurement and the frequency and measurement time is largely reduced. To obtain a clear and observable structure during the PIV measurements the injection mass was increased during the measurements that were conducted at $Re = 300$.

5.3.2 The mass percentage of injection

The mass percentage that is injected is calculated by using equation (5.1)

$$\frac{Q_{inj}}{Q_{pipe}/100} = \frac{A_{inj}u_{inj}}{A_{pipe}u_{b}/100} = \frac{\pi \cdot D d_{inj} u_{inj}}{\frac{1}{2} \pi D^2 u_{b}/100} = \frac{d_{inj} 100 \cdot 4 u_{inj}}{D u_{inj}} = 5 \frac{u_{inj}}{u_{b}} \% \quad (5.1)$$
Table 5.1: Overview of the camera frame parameters.

<table>
<thead>
<tr>
<th>Re</th>
<th>Frame mode</th>
<th>Frame rate</th>
<th>Time between frames</th>
<th>Nr. of frames</th>
<th>Measurement time</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>Single frame</td>
<td>200.00 Hz</td>
<td>0.005 s</td>
<td>3138</td>
<td>15.69 s</td>
</tr>
<tr>
<td>15000</td>
<td>Single frame</td>
<td>1279.00 Hz</td>
<td>7.8·10^{-4} s</td>
<td>3139</td>
<td>2.45 s</td>
</tr>
<tr>
<td>35000</td>
<td>Double frame</td>
<td>639.5 Hz</td>
<td>15.6·10^{-4} s</td>
<td>1570</td>
<td>2.46 s</td>
</tr>
</tbody>
</table>

Where $Q_{inj}$ is the volume flow through the slit of the injection chamber and $Q_{pipe}$ is the volume flow through the pipe. Furthermore, $D$ is the inner pipe diameter, $d_{inj}$ the injection slit width and $u_{inj}$, $u_b$ and $u_p$ are the velocity of the injection, the bulk speed and the piston speed respectively. Finally $A_{inj}$ and $A_{pipe}$ are the area over which the fluid is injected and the cross-sectional area of the pipe. The piston speed is calculated using $u_p = 0.07 \cdot u_{inj}$. The relatively large disturbance, 95% of the mass flow through the pipe, is performed to ensure that the instantaneous result of the injection is captured. This measured result is further discussed in chapter (6) and more specifically in subsection (6.2.1). For the measurements a $Re = 15000$ and $Re = 35000$ a ratio has been chosen of 1.25% and 2.5% with respect to the bulk speed of the pipe. This is done since a disturbance of the flow normally is performed around 5% with respect to the bulk flow. However, an injection of this percentage at $Re = 15000$ and $Re = 35000$ would ask for stronger injection pumps. The test-matrix for $Re = 300, 15000$ and $35000$ is displayed in table 5.2 and table 5.3. Table 5.1 is containing other relevant parameters in the experiments.

5.3.3 Injection chamber feeding tubes stagnation pressure

To ensure that the tubes would not detach from the injection chamber during an injection, the stagnation pressure is calculated using equations 5.2, 5.3, 5.4, 5.5 and 5.6. As a reference the stagnation pressure during other injection experiments\textsuperscript{18} is used which ranges between 0.03 and 306.6 Pa. The stagnation pressure in the tubes is calculated based on the injection width, the injection velocity and the bulk velocity.

\[
\begin{align*}
  u_{inj} &= \frac{u_b}{100}\beta\% \quad (5.2) \\
  Q_{inj} &= A_{inj}u_{inj} \quad (5.3) \\
  Q_{tube} &= \frac{Q_{inj}}{6} \quad (5.4) \\
  u_{tube} &= \frac{Q_{tube}}{A_{tube}} \quad (5.5) \\
  P_{stag,\text{tube}} &= \frac{1}{2}p\nu_{tube}^2 \quad (5.6)
\end{align*}
\]

where $u$, $Q$, $A$ and $P$ are the velocity, volume flow, the area and the pressure respectively, for the position at the injection slit ($inj$), the tube ($tube$) and for the bulk flow ($b$). The
maximum stagnation pressure in the tubes is calculated to be 0.7 Pa, which is calculated for an injection width of 0.5 mm and for an injection velocity of $\beta = 2.5\%$ with respect to the highest bulk velocity at $Re = 35000$. This pressure is below the maximum values that were determined for the injection system during earlier measurements$^{18}$.

Table 5.2: Test-matrix of the $Re = 300$ set.

<table>
<thead>
<tr>
<th>$Re$</th>
<th>$u_b$</th>
<th>$u_{inj}$</th>
<th>$u_{inj}/u_b$</th>
<th>$u_p$</th>
<th>$\frac{Q_{inj}}{Q_{pipe}}$</th>
<th>Injection time</th>
<th>Nr. of repetitions</th>
<th>Measurement range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm/s</td>
<td>mm/s</td>
<td>%</td>
<td>mm/s</td>
<td>%</td>
<td>s</td>
<td></td>
<td>s</td>
</tr>
<tr>
<td>300</td>
<td>7.53</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>2x</td>
<td>0 &lt; $t &lt; 15$</td>
</tr>
<tr>
<td>300</td>
<td>7.53</td>
<td>142.80</td>
<td>189</td>
<td>10</td>
<td>95</td>
<td>$t = 0$</td>
<td>2x</td>
<td>$-3 &lt; t &lt; 12$</td>
</tr>
<tr>
<td>300</td>
<td>7.53</td>
<td>142.80</td>
<td>189</td>
<td>10</td>
<td>95</td>
<td>$t = 0$</td>
<td>2x</td>
<td>$10 &lt; t &lt; 25$</td>
</tr>
<tr>
<td>300</td>
<td>7.53</td>
<td>142.80</td>
<td>189</td>
<td>10</td>
<td>95</td>
<td>$t = 0$</td>
<td>2x</td>
<td>$22 &lt; t &lt; 37$</td>
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<tr>
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<td>$35 &lt; t &lt; 50$</td>
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Table 5.3: Test-matrix of the $Re = 15000$ and $Re = 35000$ set.

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<thead>
<tr>
<th>$Re$</th>
<th>$u_b$</th>
<th>$u_{inj}$</th>
<th>$u_{inj}/u_b$</th>
<th>$u_p$</th>
<th>$\frac{Q_{inj}}{Q_{pipe}}$</th>
<th>Injection time</th>
<th>Nr. of repetitions</th>
<th>Measurement range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm/s</td>
<td>mm/s</td>
<td>%</td>
<td>mm/s</td>
<td>%</td>
<td>s</td>
<td></td>
<td>s</td>
</tr>
<tr>
<td>15000</td>
<td>376.50</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>-</td>
<td>2x</td>
<td>$0 &lt; t &lt; 2.45$</td>
</tr>
<tr>
<td>15000</td>
<td>376.50</td>
<td>94.13</td>
<td>1.25</td>
<td>6.59</td>
<td>1.25</td>
<td>$t = 0$</td>
<td>10x</td>
<td>$0 &lt; t &lt; 2.45$</td>
</tr>
<tr>
<td>15000</td>
<td>376.50</td>
<td>188.25</td>
<td>2.50</td>
<td>13.18</td>
<td>2.50</td>
<td>$t = 0$</td>
<td>10x</td>
<td>$0 &lt; t &lt; 2.45$</td>
</tr>
<tr>
<td>35000</td>
<td>878.50</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>-</td>
<td>2x</td>
<td>$0 &lt; t &lt; 2.46$</td>
</tr>
<tr>
<td>35000</td>
<td>878.50</td>
<td>219.63</td>
<td>1.25</td>
<td>15.37</td>
<td>1.25</td>
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<td>10x</td>
<td>$0 &lt; t &lt; 2.46$</td>
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<tr>
<td>35000</td>
<td>878.50</td>
<td>439.25</td>
<td>2.50</td>
<td>30.75</td>
<td>2.50</td>
<td>$t = 0$</td>
<td>10x</td>
<td>$0 &lt; t &lt; 2.46$</td>
</tr>
</tbody>
</table>
Chapter 6

Analysis

The ink visualisations are conducted only at $Re = 15000$ and $35000$ since the rotation inside the core of the generated vortex at $Re = 300$ cannot be clearly recognised due to the very low bulk velocity and its corresponding injection velocity. Therefore, during the SPIV measurements the injection velocity at this Reynolds number is increased to an amount of 95% with respect to the bulk velocity. The ink visualisations are conducted to monitor the progression and position of the generated vortex in time. This will be used to decrease the amount of data that has to be stored in the cameras to capture the vortex. This information furthermore generates a feeling for what is happening during the injection. Moreover, it is used to see if a vortex has been generated.

6.1 Results of the dye visualisation

6.1.1 Influential factors on the generated shape of the vortex

The injection slit width

The first installed vortex generator contained an injection width of $d_{inj} = 1$ mm. At this injection width, the generation of coherent vortex structures could not be generated. Thereafter, the injection width was decreased to its final dimension of $d_{inj} = 0.5$ mm. During the experiments with this configuration, hairpin vortices appeared at $Re = 15000$. They are clearly visible as dark blue structures against the lighter blue background, as displayed in figure 6.2(a). The structures are formed within one pipe diameter while travelling downstream and are coherently convected downstream for at least 30 pipe diameters. At that location, the rotation of the dye inside the core of the structures is still clearly visible.
Air in the injection chamber

During the injection with dye a trapped air bubble was discovered at the top part of the injection chamber. Due to the air-bubble the water pressure, through the upper part of the injection chamber will decrease. Accordingly, the injection over the slit will be non-uniformly distributed. Moreover, the injection velocity at the lower part will be higher than the injection velocity at the upper part. Therefore, the vortex at the lower half of the pipe has the opportunity to stay attached to the slit for a longer time, while the upper vortex is shed at an earlier stage. This is a direct result of the shedding angle which is obtained at lower injection velocities. This mechanism is displayed in figure 2.2 and has been further elaborated on in section 2.3.2. As a result, the shed vortex is partly stretched by the larger injection from the lower side of the pipe. The ring is stretched and forms an omega shaped hairpin vortex, since it is partly connected to the injection slit. A downstream convection will follow as indicated in figure 6.1 forming a hairpin structure as displayed in figure 6.2(a). The generated vorticity at the lower part of the pipe will either follow later on, or will dissipate into heat as the hairpin legs are stretched downstream where in the limit they will detach from the injection slit.

As the sealing of the injection chamber was improved, it became possible to inject in a more homogeneous manner. This finally generated the closed ring vortices that are of interest to study the velocity mechanism between small and large scale structures. Other more chaotic appearing hairpin vortices are observed as well. They following the closed ring more or less one pipe diameter behind as displayed in figure 6.2(b). It is assumed that these are entrainment vortices counteract the motion of the ring-vortex. This assumption is supported by the iso-contour plots of the velocity fields in section 6.2.2, derived from 3D SPIV data.
6.1 Results of the dye visualisation

(a) Two injected hairpin vortices indicated by number 1 and 2.

(b) A vortex ring indicated by number 1.

Figure 6.2: Injected coherent structures, flow from right to left.

6.1.2 The four phases during the dye visualisation at $Re = 15000$

During the flow visualisation it is important to locate the actual generated large scale coherent structure since the measurement time will be much shorter, than the time needed for the structure to convect through the measurement plane. During the PIV measurements conducted at higher Reynolds numbers the frequency of the camera recordings will be higher and the memory will therefore be filled in a shorter time. During the injection with ink, 4 phases were distinguished. The first phase, before injection, displays straight, very lightblue streaks. These are formed by the diffusion of stationary ink from the injection chamber into the pipe, where it is convected downstream. The streaks that stay visible, also stay close to the wall. The second phase is characterised by the appearance of the large scale hairpin vortex figure 6.2(a) or the large scale vortex ring as indicated in figure 6.2(b). This structure is then followed up by its hairpin legs or quasi stream-wise vortices, which is defined as the third phase. The fourth phase follows more or less one pipe length behind the third phase. It has a more chaotic character. The relatively ordered flow is now suddenly triggered into an energetic flow that contains many, smaller whirls that show a very active movement throughout the entire
cross-section of the pipe. The idea was formed in the prior literature study\textsuperscript{45} that this more chaotic structure could be formed due to entrainment vortices that are expected to be part of, and connected to, the initiated, larger scaled, vortex. These structures are expected to entrain the water that is flowing at the backside of a hairpin vortex. In other research it is measured that the decay of a vortex ring does not develop gradually but rather in steps\textsuperscript{46}. This adds to the hypothesis made in this thesis that these opposite rotating vortices, with respect to the main ring vortex, are absorbed at the back of the vortex and thereby decreasing its strength in vorticity in steps. Due to the introduction of fluctuating instability by these counter rotating vortex rings to the core of the main vortex, this core will be shedding part of its vorticity downstream. This could be the cause of the stepwise decay of its vorticity in time as indicated in figure 6.3.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure6.3}
\caption{Circulation and propagation speed $Re = 7500$ in comparison to the propagation speed of laminar ring vortex\textsuperscript{46}. An indication of the intake of counter rotating entrainment rings, by the main ring vortex, at its back-side.}
\end{figure}

\subsection{Results of the dye visualisation at $Re = 300$ and $35000$}

In section 5.1.1 an increase of the velocity gradients closer to the wall with respect to the laminar flow regime was displayed. This indicates that generated structures will have more difficulties to form and convect to the centre of the pipe. This effect is observed during the ink visualisation at $Re = 35000$, where the dye is very rapidly diffused towards the sides of the pipe wall. The injection resulted into a wide spread puff of rather light coloured blue
water. The ink was located close to the wall of the pipe. It indicates, that the effect of the injection onto the core of the turbulent flow had been reduced. This is in line with the expected result, since the mass percentage of the injection that is applied at $Re = 15000$ is reduced by almost 90 percent as indicated in tables 5.2 and 5.3. The answers to the questions whether or not a vortex will be generated and where it is located in time, are already obtained by the visualisations that were conducted at $Re = 15000$.

6.1.4 Limitations and considerations when using dye visualisation

Attention has to be given to the fact that an ink visualisations could be deceiving. The ink can still maintain the shape of the vortex while the vorticity itself has already been diffused. Therefore, it is always checked if the ink inside the core of the coherent structure is still rotating during an experiment. In addition, the ink is rapidly diverging when it is injected into a turbulent environment. This makes it hard to conclude whether or not the injected vorticity is still partly present or not. An other problem to cope with is the breaking of the light through multi media which is causing the images to deform. The intensity with which this is happening strongly depends on the angle that is used with respect to the pipe. Furthermore, only a few measurements can be conducted before the water in the pipe at the test section itself becomes coloured with dye. This reduces the visibility and time has to be invested to refill the facility with clean water. Additionally, the dye should be neutrally buoyant and should have a high stability against mixing\(^{47}\). Care should be taken, to avoid the use of ink that contains poisonous or reactive substances that might damage parts of the flow facility. Since the created structures are moving with a velocity through the pipe the camera should have a very short shutter time which means that the light should be increased in intensity to be able to record a good image.

Although visualization tools are interesting, the effectiveness of a visualization depends on perception, cognition, and the users specific tasks and goals. How a viewer perceives an item in a visualization display depends on many factors, including lighting conditions, visual acuity, surrounding items, color scales, culture, and previous experience\(^{48}\).
6.2 Results of the SPIV measurements

6.2.1 Comparing Labview input with measured mean velocity SPIV values

(a) The cross-sectional averaged out-of-plane velocity over time as measured by SPIV.

(b) The designed velocity function of the injection over time

Figure 6.4: Comparing the measured SPIV velocities to the velocity function of the injection over time.

The desired injection velocity properties described in section 2.3.2 are the basis for the shape of the injection. The acceleration effect of the injection at Reynoldsnumber 300 is clearly recognised partly due to its distinctive shape. Note that in figure 6.4(b), the negative value of the motion of the transverse leads to a positive output at the injection chamber. Figure 6.4(a) displays the increase of the cross-sectional averaged velocity, associated with the injection. In
the function that is put in Labview one can see the similar acceleration and deceleration of
the flow over the time of the injection. The function of the injection velocity in time can be
controlled for both injections. This creates the opportunity to modify the time between two
hairpins, so that different cases of interactions between vortices can be studied. For instance,
a faster hairpin can be generated that captures the slower hairpin vortex that was generated
in front of it.

6.2.2 Laminar results

The laminar RMS values

At Reynolds number 300 the flow is laminar and stationary. Therefore, the RMS values of
the velocity can be interpreted as PIV correlation noise. The RMS values of the in plane
velocity fluctuations are plotted against the x- and y-axis in figure 6.5. At the right side the
fluctuations, expressed in pixel units, are displayed. The velocity fluctuations are normalised
by the maximum out-of-plane velocity. The maximum deviation of the RMS values is for the
velocity component in the x-direction, which is approximately 3 times higher than the results
obtained by C. van Doorne\textsuperscript{18}. However, the pixel size equals 11 \(\mu\)m. Thus a displacement of
0.25 pixels \(\approx 2.75\mu\)m, is the size of 1/36 of a human hair\textsuperscript{19}.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure6.5.png}
\caption{RMS values of the three velocity components for measurements conducted at \(Re=300\).}
\end{figure}
Acrilate is known to absorb 0.29 - 0.42% water\(^{50}\). In section A.3 more refined information can be found about the production of the used calibration glass and the newly designed and produced high-tech calibration glass. The window size is chosen such to give less than 5% outliers in the velocity vector field. However, a very noisy frequency is present after the post processing is performed. The origin of these frequencies is further explored in section 6.3.2.

Contour-plots of velocities in 2D representation

Before proceeding with the analysis of the contour-plots, it is noted that a positive \(x\)-direction is in the cross-sectional plane perpendicular to the \(y\)-direction that is positively pointing upward. Using the right hand rule, the positive \(z\)-axis is pointing in downstream direction. Analysis of these figures as opposed to fully three-dimensional plots, can be done in a more easy way, when looking for the extremes of the velocity. The contours are made in two perpendicular planes that intersect each other in the line that runs through the centre in the length of the pipe. Furthermore, they are oriented in the direction of the \(x\)- and \(y\)-axis.

During the first measurement that starts approximately 3 seconds before the actual injection, two patterns are identified. These patterns are displayed in figure 6.6, they are the direct effect onto the pipe flow caused by the injection that is performed two times shortly after one another. It indicates that the injection of fluid mass is increasing the out-of-plane velocity also closer to the wall. The increased velocities are present in the form of a wedge that contains different layers of velocity contours.

Moreover, figure 6.6 indicates that the velocity in the core of the structures is almost twice as fast as the bulk velocity. This is the effect of the direct displacement of the incompressible mass in front of the test section by the injected mass super-imposed onto the flow in the pipe. Additionally, the effect of the injection on the velocity profile at the measurement section is a naturally distributed velocity in a round bell shape. It is increasing the velocity more at the centre than to the areas close to the wall. This information can be deduced from figure 6.6. The typical configuration of the multiple velocity layers, as displayed in figure 6.6, is recognised as a characteristic of ring vortices. Ring vortices are accelerating the flow in their center with respect to their outer side. Although two ring vortices are formed as will be shown in section 6.2.2 figure 6.12, these are not the coherent ring structures that were desired to be studied. Since a much larger injection is done of 95% with respect to the bulk flow, multiple vortices could be generated during a single injection. This generates a way for trains of hairpins to arise.

In equation (3.17) of section 3.2.6 it is calculated that the actual structures would arrive after 21.4 seconds. When analysing figure 6.9 of the measurement that is conducted 22 seconds after the injection, a multiplicity of iso-velocity cells, belonging to coherent structures is clearly present. These structures decrease the earlier obtained high velocity in the flow and mix this high velocity flow over the rest of the cross-section. This effect can be observed in the second plot of figure 6.7(b).

This accelerated flow is created by the generated vortex at an earlier stage. This single and large structure is displayed in figure 6.8. The large difference in velocity can be explained by the large injection velocity that is used for the laminar flow case. The injection velocity super-imposes itself onto the bulk velocity. In this way that the structures are convected downstream by the bulk velocity twice as fast.

In figure 6.7 the structure that is found 10 seconds after injection is relatively large and
isolated in the flow. In size, it is proportional to the pipe radius. The locations where the flow is stagnating are inspected. One can recognise from the upper sub-plot of figure 6.7(b), that a stagnation area has been formed. This figure plots a vertical plane that runs through the centre of the structure that is displayed in figure 6.8. Furthermore, the horizontal plane runs through the centre of this structure as well. The structure is located at the region around coordinate \((z/D = -2, y/D = -0.1)\). In the second sub-plot there is a region in front of this area where the vertical velocity is pointed upward. Behind this area a region exists with down-flow. Therefore the area in between has to be stagnated in the \(y\) direction. Moreover, it displays a stagnation around the coordinate \((z/D = -0.6, y/D = -0.5)\).

Looking into the lowest sub-plot of figure 6.7(a), one has to note that this horizontal plane is located at the centre of the vertical planes of the plots to its right. The plot is showing a high velocity flow indicated by a bright, yellow colour. This area is generated by the head of a hairpin vortex and its legs. The accelerated flow is slowed down closer to the front side of the structure, at the coordinates \((z/D = -2, -0.2 < x/D < 0.2)\). Here the low velocity is impinging on its vortex bubble.

An other interesting feature is discovered in the middle sub-plot of figure 6.7(a). It displays a plane that contains a cross section of both hairpin legs of the hairpin vortex. The cores of the legs are located at the coordinates \((z/D = -2.3, y/D = 0.1)\) and \((z/D = -2.2, y/D = -0.2)\). The deduced information from this plot supports the hypothesis that is proposed in this work, that inside a hairpin vortex core a preferable flow direction is present. This can be
(a) The x-z plane. (b) The y-z plane.

Figure 6.7: Iso-velocity surfaces indicating the presence of a hairpin vortex, flow from right to left, measurement time: 10 – 25 seconds after injection, as predicted in equation (3.17), $Re = 300$.

Figure 6.8: The combined SPIV information into a 3D hairpin structure. The double arrow indicating the vortex direction, the blue area the low velocity flow, the grey area the vortex bubble and the $\beta$ the horizontal orientation angle of the hairpin with respect to the local flow direction.

appreciated by the change of the sign of the y-velocity component in the middle sub-plot of figure 6.7(a).

Additionally, the third sub-plot of figure 6.7(a) shows that these hairpin legs are connected horizontally. Looking at the out-of-plane flow characteristics one can find a "bridge" over which the flow is accelerated at coordinates $(z/D = -2, -0.2 < x/D < 0.2)$. This typical
6.2 Results of the SPIV measurements

The effect can be coupled to the presence of a hairpin head. Moreover, the presence of the hairpin head is visible in the middle sub-plot of figure 6.9(b), where it generates an up-wash (bright yellow) in front of the structure that is gradually turned into a down-wash at the back of the structure (blue). Finally, from the last plot in figure 6.9(b) it is noted that the out-of-plane flow, inside the vortical structure is boosted (bright yellow) from its lower back-side. This is to be expected since the hairpin is feeding on this high energy flow. An overall 3D impression of the flow is given in figure 6.8.

The structures, present 21.4 seconds after injection, are closely packed together, in a similar way as is displayed in figure 5.4(b). They form a train of hairpin vortices. This phenomenon is further explained in section 5.2.1. The identification of these hairpin vortices is based on a comparison that is made between the first sub-plot of figure 6.7(b) and the first sub-plot of figure 6.9(b). In that plot of figure 6.7(b) a velocity pattern is recognised that belongs to a hairpin vortex. This pattern is recognised at a smaller scale in the first sub-plot of figure 6.9(b). Moreover, the pattern occurs sequentially at three locations (yellow), indicated by the coordinates \((z/D = 1.5, y/D = 0.4), (z/D = -0.6, y/D = 0.4)\) and \((z/D = -0.2, y/D = 0.4)\).

Moreover, multiple locations are recognised in which the low-velocity flow is swept upward, this can be coupled to the footprint that hairpin heads create. This effect is observed at coordinates \((z/D,y/D) = (-1.5,-0.4), (-1.1,-0.4), (-0.8,-0.4)\) and \((-0.5,-0.3)\). In addition, it can be noted how the legs of the hairpins located at \((z/D = -1.5, x/D = -0.3)\) and \((z/D = -1.35, x/D = 0.3)\) are connected by their hairpin heads. These structures decelerate the flow in the centre and evenly mix the momentum of the flow towards the wall of the pipe. This is recognised in the last sub-plot of figure 6.9(b). In the figure a deceleration of the flow is noted at location \(z/D = -1.5\), where the sudden spreading of the momentum occurs away from the centre. Furthermore, a second hairpin decelerates the flow, over almost the entire cross-section, at \(z/D = -0.5\). This indicates that the presence of relatively smaller scaled entrainment vortices are counteracting the motion of the generated larger-scale vortex.

Finally, an interesting phenomena is recognised when the last sub-plots of figures 6.7(b) and 6.9(b) are connected. These plots are chronological and display how the generated large-scale hairpin is connected, via the bright-yellow iso-velocity surface, to the entrainment vortices at a later stage. This result supports the hypothesis that the multiple, small-scaled entrainment vortices are counteracting the motion of the generated larger-scale hairpin vortex. A 3D impression of these entrainment vortices is presented in figure 6.10.
Figure 6.9: Iso-velocity surfaces indicating the presence of a train of hairpin vortices, flow from right to left, measurement time: 22-27 seconds after injection at $Re = 300$.

Figure 6.10: Impression of the hairpin trains in 3D based on the SPIV iso-velocity fields at $Re = 300$, double arrows in green indicate the counter rotating vortex orientation. Furthermore, the blue area indicates low velocity flow.

Ring vortices

Indicated in section 6.2.2, figure 6.12 displays two 3D rings, which are not the actual coherent structures of interest. The reason why these structures appear is the following. During
injection, the injected fluid is accelerating an incompressible volume of water. This results into an instant acceleration and deceleration locally at the measurement section.

![Figure 6.11](image1.png)

**Figure 6.11:** The two ring vortices, detected using the $Q$-criterion at $Re = 300$

![Figure 6.12](image2.png)

**Figure 6.12:** The indicated vortex stretching $R$ of the two rings at $Re = 300$

At that instant the form of the acceleration is measured in the shape of a vortex ring. It
is noticed that the rings vary in their own core radius thickness, being the thinnest at the top and bottom. This can be clarified, since the inner side of the injection chamber contains two flanges. It is at these locations that the thin walled cylinder is supported by two flanges. These separate the injection chamber into two sections. They furthermore function to keep the vortex generator from moving forward during an injection. Therefore, the mass-flow, and thereby the velocity on the middle upper and lower attachment points, is significantly lower, with respect to the sides at the top and bottom location of the pipe. As a result, a thicker “vortex” shape will develop, further away from these flanges. Furthermore, the shape of these rings is contained within a plain perpendicular to the length of the pipe. This is to be expected since the injection is done in a perpendicular plane as well.

6.2.3 Turbulent results

The mean profile of the out-of-plane velocity \(< U_z >\), for the measurements performed at \(Re=15000\) is displayed in figure 6.13. It is the profile of a measurement that is performed without injection. On the left y-axis the velocity is normalised by the friction velocity \(u_{*1}\). This velocity is obtained by the relation between the bulk velocity \(U_b\) and the Fanning friction factor \(f\), provided in equation (6.1).

\[
u_{*1} = U_b \sqrt{\frac{1}{2} f} \tag{6.1}\]

The value for the Fanning friction factor \(f\) for flows where \(2100 < Re < 10^5\) is determined by the Blasius-friction-law that holds for these turbulent pipe flows\(^{51,52}\).

\[
f = 0.079 Re^{-\frac{1}{4}} \tag{6.2}\]

At \(Re = 15000\) the bulk velocity \(U_b = 376.5\) mm/s. Consequently, \(f = 0.00713\) and \(u_{1*} = 22.48\) mm/s. Figure 6.13 displays a larger velocity profile than the expected mean velocity of 376.5 mm/s. Therefore, figure 6.14 displays all mean velocities profiles over the entire cross-section so that the cause of this deviation can be traced back.

Figure 6.14 displays a profile for which the values for \(< U_x >\) and \(< U_y >\) are increased significantly. This indicates that the laser-plane could have been changed from a perpendicular orientation to the pipe into one in which an angle has been introduced. Moreover, the values of \(< U_y >\) contains a negative part and graph of \(< U_z >\) displays an asymmetric profile. This indicates that the laser-plane might have an offset with respect to the plane in which its calibration was done.

The change in the angle can be countered by making use of Euler rotation matrices. The Euler rotation is defined by equation (6.3).

\[
U_{Eu} = [B]_{Eu}[C]_{Eu}U \tag{6.3}\]

Where:

\[
[B]_{Eu} = \begin{pmatrix}
\cos(\theta_{Eu}) & 0 & -\sin(\theta_{Eu}) \\
0 & 1 & 0 \\
\sin(\theta_{Eu}) & 0 & \cos(\theta_{Eu})
\end{pmatrix}
\]
and:

\[
[C]_{Eu} = \begin{pmatrix}
1 & 0 & 0 \\
0 & \cos(\psi_{Eu}) & \sin(\psi_{Eu}) \\
0 & -\sin(\psi_{Eu}) & \cos(\psi_{Eu})
\end{pmatrix}
\]

are the rotation matrices of Euler. Furthermore, \( U_{Eu} \) is the new obtained 3D velocity vector. The Euler rotation angles \( \theta_{Eu} \) and \( \psi_{Eu} \) determine the amount over which the vectors are rotated with respect to their rotational axis. These angles indicated that large angles of deviation had to be present since \( \theta_{Eu} \approx 11.5^0 \) and \( \psi_{Eu} \approx 4.3^0 \). This should have been clearly seen during the set-up and therefore it indicates that the optics had to be altered accidentally.

The effect of the Euler rotation on the velocities is displayed in figure 6.15. However, the correction of the asymmetric profile will be very complex. Furthermore, the results for the RMS values are so much deviating from their normal values that they are not presented here. Nonetheless, the velocities have been measured within this plane and their values are known. Therefore, iso-velocity surfaces can still provide information about the structures that are present. These graphs will be presented to study how the velocity field is responding to the injection.

![Mean streamwise velocity profile, at Re=15000.](image)

**Figure 6.13:** Mean streamwise velocity profile, at \( Re=15000 \).

First the velocity iso-contours are plot in the x- and y-direction to look for obvious patterns that indicate the appearance of the injected coherent structure. The iso-velocity plots are displayed in figure 6.16. An amount of 90% of the mean velocity of the zero measurement is subtracted from each of the files where the injection is applied during the measurement.
Figure 6.14: Mean velocity profiles, in-plane $U_x$ and $U_y$ and out-of-plane $U_z$, at $Re=15000$.

Figure 6.15: Mean velocity profiles, in-plane $U_x$ and $U_y$ and out-of-plane $U_z$ corrected by the Euler rotation, at $Re=15000$.

This eases the recognition of the presence of a generated, large-scale, vortex. However, figure 6.16(a) and 6.16(b) display that a clear indication of an injected vortex is absent. The reason of this result could be found in the fact that the injection velocity had not been large enough,
6.2 Results of the SPIV measurements

(a) The $x$-$z$ plane.

(b) The $y$-$z$ plane.

Figure 6.16: Iso-velocity surfaces, 6.59 mm/s injection, flow from right to left, measurement time: 2.45 seconds, at $Re = 15000$.

or that the vortex arrival time had not been predetermined accurately enough. Furthermore, it should be noted that the position of the injection mechanism had been moved to the front of the test section, after the visualisation methods were completed. This might have caused instability to the generated structures, on the location where the transition from the vortex
generator to the test section is made. At $Re=15000$, a generated structure that becomes unstable would therefore be resolved before it could be detected at the test section.

**Navigating through the pipe using a 3D tool**

However, since the 3D coherent structures are formed on the inside of the pipe wall the view can quickly become obscured by them. Therefore, a 3D tool is used to increase the possibilities to inspect the structures in 3D. Two existing Matlab programs\textsuperscript{53,54} are combined and adapted to realise the compatibility between the software of the 3D mouse and Matlab. In this way the "SpacePilot Pro"\textsuperscript{55} is one of the available tools that can be used with the program to navigate through the 3D environment. It greatly increases the opportunity to investigate the structures when viewing from the inside out through the pipe.
6.2 Results of the SPIV measurements

(a) The $x$-$z$ plane.

(b) The $y$-$z$ plane.

Figure 6.17: Iso-velocity surfaces, 13.18 mm/s injection, flow from right to left, measurement time: 2.45 seconds, at $Re = 15000$ 80\% subtracted bulk velocity.
6.3 Performance

6.3.1 The camera software

For the post processing of data, the 8.0.3 version of the Lavision Camera software is used.

Figure 6.18: Correct result of a conducted measurement showing a more or less constant mean values of the velocities over time.
6.3 Performance

(a) Sudden loss of correlation for multiple pairs of measured planes causes sudden drops in mean velocity for $t < 1.7$ sec.

(b) Repetition of images causes a repeatable pattern of the averaged total $\omega_z$ in the measurements mostly from time $t > 1.7$sec.

**Figure 6.19**: The transition of the two software problems
The graphs, representing the mean velocity with respect to time at \( \text{Re} = 35000 \), contain sudden decreases. This corresponds to PIV image pairs that contain a sudden drop in correlation. They possess only a few relatively large velocity vectors, which makes it easy to detect them visually. As a result, the mean velocity locally reaches a very low value. A correct series of measurements is compared with the measurements that contain errors. This can be accomplished by comparing figure 6.18 with 6.19(a) respectively. It can be recognised that the errors occur suddenly and irregularly. When regarding the raw data of the camera frames at these moments, the particle tracing by eye, which is normally possible, was excluded. Occasionally, the particles of only a fraction of two recorded images was traceable. In addition, for all sets of \( \text{Re} = 35000 \) the errors disappear at \( t > 1.75 \) seconds. This correspond to a number of files larger than 112. This hints to an error in the camera or storage software.

Later on, it was discovered that an other error is taking over the correlation error. This is observed when the total vorticity is plot against time. The plot is displayed in figure 6.19(b), it displays a repetitive pattern. Therefore, the first two lower peaks of this repetitive pattern in file: “\( \text{Re}=35000, \) measurementnr.5, \( 15.37(\text{mm}) \) injection corrected, Vortex Ring Detection”, are investigated. The two points \((\omega, t) = (1.3744, 1905) \text{ and } (1.4773, 1905)\) the corresponding file is traced back. Since the \( \Delta t \) corresponds to 0.00156 s their corresponding file-numbers can be traced back to number 880 and 946. Row 64604, in both files, gives a similar unique combination of the velocity values of \( u = 0.143856 \) m/s, \( v = 0.030630 \) m/s and \( w = 2.313585 \) m/s.

Therefore, the raw images are investigated, which proved to be the exactly the same. The repetitive pattern of the vorticity corresponds to a repetition of the same 66 raw images, in the same order. These kinds of errors are very hard to detect by observing the raw images. As a reference, figure 6.18 displays the bulk velocity as it should appear over time. The amount of files that a camera can store is larger then the set that contained the errors. Therefore, the error is once more traced back to the storing procedure of the images. This is carried out in the memory of the cameras, and is furthermore depending on its software.

### 6.3.2 Frequency of the pump

The first measurement of the bulk velocity at \( \text{Re} = 300 \) seems to contain an added constant sinusoidal disturbance. Since the pump is operated under a relatively low Reynolds-number it is thought that this frequency might be initiated by the pump. To investigate this effect a Fast Fourier Transform (FFT) of the bulk velocity of the first measurement is done, to this aim equations (6.4), (6.5) and (6.6) are combined.

\[
    f_s = \frac{1}{h} \quad (6.4)
\]

\[
    T_m = N \cdot h \quad (6.5)
\]

\[
    f_0 = \frac{1}{T_m} \quad (6.6)
\]
Figure 6.20: Bulk velocity signal (top) and corresponding power spectrum (bottom), where the frequency of the pump is recognised at the location of the high peak.

Figure 6.21: Total bulk velocity signal compared against the pump signal
Where, \( N = 2^{10} \), \( h = 0.015 \text{ s} \), \( f_s = 66.67 \text{ Hz} \), \( f_0 = 0.065 \text{ Hz} \) and \( T_m = 15.36 \text{ s} \) are the number of sample points, the time per sample, the sampling rate, the base-frequency and the total measurement time respectively. Furthermore, \( S_{u_z\text{-tot}} \) is the auto-spectral density in \( \text{mm}^2\text{s}^{-2}/\text{Hz} \). It can be expressed as:

\[
S_{u_z\text{-tot}} = \frac{1}{(N|\text{FFT}(w_{\text{mean}})|^2)}
\]

The absolute value is taken here to obtain only the real value of the auto-spectral density. This gave a high amplitude at 0 Hz which can be coupled to the mean flow. This peak is set to zero. Moreover, it gave a second peak at 26.8 Hz.

It is a relative low frequency that could be linked to a disturbance initiated by the pump as displayed in figure 6.20. Its amplitude and frequency were found by searching for the maximum value of \( S_{u_z\text{-tot}} \). When the exact location of the peak due to the pump is obtained as it is displayed in figure 6.20, it is set to zero. Thereafter, the Inverse Fast Fourier Transform (IFFT) is performed to obtain the residual signal in time domain. In addition, the Signal to Noise Ratio (SNR) is calculated to give a value of 12.9322 dB, which is a rather low value which again indicates that there could be an error in the used cameras or the software of the cameras. One can recognise the sine wave inside the signal of the upper sub-plot of figure 6.21. The lower sub-plot is displaying the signal of the pomp as it is obtained by the IFFT of the pomp-frequency (\( \approx 27 \text{ Hz} \)), the peak displayed in figure 6.20.

When the signals are subtracted one can find that the difference is still relevant. This frequency is not filtered out, however structures operating at this frequency will be ascribed to noise. Furthermore, its residual is plotted against time and is smoothed to look for new obvious patterns which were not present. Finally, the noise is suppressed in Matlab by making use of a regression method which takes 2 points on the left and right of each point in \( x \) and \( y \) direction and 3 at the front and back in \( z \) direction.
In this thesis, a device is developed that can generate large scale coherent structures, which can be injected in a controlled manner and studied with respect to the turbulent structures that are naturally contained in the flow. This device is called a vortex generator since it is triggering role-up over a circumferential flange to generate a vortex during the injection. This chapter contains the obtained knowledge on how the controllable injection parameters influence the characteristics of this generated vortex. In addition, it discusses a relation that was observed between the injected large-scale vortex, measured 10-25 seconds after injection and, multiple, small-scaled structures, measured 22-27 seconds after injection.

7.1 Parameters that determine the characteristics of the generated vortex

Parameters that play an important role in the shape of the generated structures are the bulk velocity $u_b$ and the injection velocity $u_{inj}$, both are related to the bulk velocity percentage of the injection $\beta$ and the injection angle $\alpha_{inj}$ in time, that influences how the vortex will be generated and shed.

The injection width $d_{inj}$ and the height of the vortex roll-up triggering flange $h_{inj}$ determine how precise the injection is injected in one plane, how homogeneous the injection will be and that the vortex has a favourable role-up direction respectively.

The type of the generated vortex can be changed by adjusting the amount of air that is trapped on the upper side of the injection chamber. In this manner one can modify the circumferential homogeneousness of the injection. Typically, when an air bubble is created on the upper side of the injection chamber the vortex generator is creating hairpin shaped coherent structures. When the injection chamber is vented, a homogeneous injection over the circumferential direction can be realised and ring vortices will be generated.

The frequency at which the structures are shed is depending on the single injection time $T_{act}$. This parameter has to be decreased for a larger Reynolds number used in the pipe.
higher Reynolds number increases the amount of fluctuations in the upstream bulk velocity. Therefore, the value of the injection angle can rapidly fluctuate. As a result, the vortex generator could shed multiple smaller vortices during an injection. This problem can be reduced by increasing the injection velocity $u_{inj}$.

### 7.2 Behavioural characteristics of the generated vortex

During the dye visualisations it is seen that a main structures will develop. Thereafter, a wavy pattern is present which is succeeded by a flow that contains many, rapidly moving, small-scaled structures (chapter 6). This result can be coupled to the SPIV results obtained from the measurements at $Re = 300$, where small-scale structures form trains of hairpins that encapsulate regions of flow. They cause the high velocity of the injected flow, which is concentrated at the center of the pipe, to evenly mix with low velocity flow, closer to the wall. Consequently, the maximum velocity in the pipe is reduced. This effect can be observed when the iso-contours of $U_z$ in figure 6.7(b) and figure 6.9(b) are connected in chronological order. It displays how the generated large-scale vortex (red) is propelling the high-velocity flow forward, into the low-velocity upstream ($10 < t < 25$ seconds after injection), which is counteracted by the trains of hairpins (green) that rotate in opposite direction and decrease the maximum value and concentration of the high-velocity flow ($22 < t < 27$ seconds after the injection). The injected high-velocity mass flow is stretching the large-scale generated hairpin vortex. The (green) train of hairpin structures is decreasing this driving motion and therefore it creates drag to the generated large-scale structure. Moreover, it is noted that the structures in figure 6.9 are hairpins by the observation that the middle subplot of figure 6.9(b) contains multiple peaks of swept-up low-velocity flow at coordinates $(z/D, y/D) = (-1.5,-0.4), (-1.1,-0.4), (-0.8,-0.4)$ and $(-0.5,-0.3)$. Furthermore, the large-scale structure, observed in the first subplot of figure 6.7(b), also appears multiple times in smaller scale in the first subplot of figure 6.9(b), the $U_x$ velocity plot in the $y$-plane. However, the clearest evidence of the counter rotating motion with respect to the large-scale vortex (red) is the fact that the green structures are not accelerating the flow but decrease its velocity by mixing it with the low velocity flow that they entrain. This effect is displayed in the last subplot of figure 6.9(b).

#### 7.2.1 Velocity characteristics of the generated large-scale vortex

What can be deduced from the SPIV measurements at $Re = 300$ is that the velocity inside the legs of a hairpin also have a preferential direction. This preferential direction is also noted to be present on top of the hairpin heads. It the vortex core of the structures show an upward and downward spiralling behaviour. Over the top of the head of the hairpins the flow is accelerated. Since the hairpin trains only entrain larger amounts of high velocity flow from one side, this flow is pushing the low speed streak upward where it could form new structures.
7.2 Behavioural characteristics of the generated vortex

7.2.2 The relation between large and small scales

In this thesis the smaller scales that follow after the larger scales are hypothesised to be generated at the front of the main large-scale structure, but are pushed aside by its vortex bubble that is formed by the vortex core. For low bulk velocities these entrainment rings that form at the front of the structures are hardly visible and are present in the form of line vortices that entrain the fluid on the backside of a vortex bubble. In other experiments, conducted at Mach = 1.7, where inertial forces are higher with respect to the viscous forces, entrainment rings were seen. Furthermore, it is observed that vorticity is entrained toward the backside of the main vortex where also the shedding of vorticity occurs. It is reasonable to conclude from this that the small-scale counter rotating entrainment rings will enter from the back of the vortex bubble and merge there with the main vortex. Therefore, the large-scale vortex ring unstable and furthermore could shed parts of its vorticity. It is assumed in this work that a large-scale ring vortex is producing multiple, smaller, counter-rotating, entrainment vortex rings, that in the limit cancel the rotation of the initially generated vortex ring. They gradually counteract the initial velocity impulse. When the propagation velocity of the generated vortex ring is large enough the counter rotating rings that emanate from its front, at higher Mach numbers, will have difficulties to enter at its back side. In the limit, when the ring is slowed down by drag, the counter rotating ring vortices will be entrained at the backside of the main vortex bubble.

7.2.3 Detailed flow characteristics of the hairpin vortex

Observing figure 6.7(a) on page 60, its coordinates at $(z/D, y/D) = (-2.1, -0.1)$ and $(-2.3, 0.1)$ display the velocity profile within the horizontal $x$-plane. The plane runs through the legs of the generated hairpin structure. An upward flow is encountered at $(-2.1, -0.1)$ which is changed into a downward motion at $(-2.3, 0.1)$. This indicates that a flow direction can be present within the core of a hairpin structure. This supports the hypothesis made in the literature study, which states that the vortex direction acts as an attractor to the velocity field. Closer to the core of the hairpin vortex this effect gets stronger. Furthermore, it is hypothesised that this attraction changes perpendicular flow lines into spiralling orbits, that themselves spiral around the vortex direction and, in the limit, will align with it. Therefore, it is interesting to investigate further what is happening, in 3D, closer to a vortex core.
This chapter contains an overview of the obtained results, which will answer part of the research questions. Furthermore, an outlook is presented, which contains other related topics of interest and new questions that have remained unanswered. Finally, the chapter closes with the recommendations.

8.1 Overview of the obtained results

The following results were obtained in this thesis:

- A non-intrusive vortex generator is produced, that can generate large-scale coherent vortical structures in a pipe flow (figure 6.2, page 53 and figure A.6, page 94).

- The flow facility has been repaired, to conduct SPIV measurements.

- A high-tech calibration glass has been re-designed and produced, which has a recognisable indication of the center target to ease the calibration procedure.

- The injection parameters, $u_{inj}$, $T_{act}$ and $T_{wait}$, that influence the development and thereby the characteristics of the generated vortices can be controlled, using the developed set-up (6.4, page 56).

- The single injection time $T_{act}$ and the time between two injections $T_{wait}$, can be modified to let two generated coherent structures interact with each other to study their interaction.

- A completely water-filled injection chamber will lead to the generation of vortex rings (figure 6.2(b), page 53).
• Allowing a certain amount of air into the injection chamber will create the condition to generate hairpin vortices (figure 6.1, page 52).

• Four phases are seen after injection, the appearance of the main large scale coherent vortex, a wavy fluctuating phase, a very active turbulent flow phase with many, small-scale, vortices and finally the recovered flow phase.

• The visualisation at $Re = 35000$ displays a fast spread of the injected dye into many small-scale eddies that are shed from the injection opening. The injection is pushed towards the wall of the pipe by the bulk velocity.

• The ratio between the upstream and the injection velocity can be controlled and determines the injection angle $\alpha_{inj}$, which influences the shedding of the vortex (figure 2.2, page 14).

• Hairpin structures can contain a flow direction inside the vortex core as displayed in the middle sub-plot of figure 6.7(a), that displays the change in vertical direction in the horizontal $x$-plane at coordinates $(z/D, y/D) = (-2.1, -0.1)$ with respect to coordinate $(z/D, y/D) = (-2.3, 0.1)$, page 60.

• The property above mentioned implies that close to the core of the vortex, streamlines should, when approaching the vortex center, orient themselves parallel to the vortex direction.

• The relative high velocity flow (bright yellow) is encapsulated by the hairpin bubble that forms a protective layer over this area, that keeps the opposing flow from entering this area (last sub-plot of figure 6.7(a) between crossection $z/D = -2$ and $z/D = -1.4$, page 60).

• The iso-velocity contours, encapsulated by structures that closely following each other, is present as a single bubble, also known in the literature as vortex pocket. This indicates that the bubbles of multiple structures connect on the inside of these structures, forming a larger union (last sub-plot of figure 6.9(b) between crossection $z/D = -1.5$ and $z/D = -0.2$, page 62).

• The present injection velocity in the turbulent case was insufficient to introduce observable, large-scale structures.

Concerning the mechanism behind the energy transfer from small- to large-scales structures, the following is observed. The structure that is generated by the vortex generator is followed by a succession of counter rotating vortices of smaller scale. The counter rotation of these small-scaled vortices can be noted by the effect they impose on the concentrated high-velocity flow, present in the last sub-plot of figure 6.9(b). In this plot the structures mix the high-velocity flow at the centre with the low-velocity that is present closer to the wall of the pipe. This counter-effect that these small-scaled vortices have on the large-scale can be observed best when the iso-contours of $U_z$ in figure 6.7(b) are put, in chronological order, to the ones in figure 6.9(b). If these counter-rotating vortices are kept from merging with the main generated vortex the more stable the generated structure will be in time. Since structures can be closely positioned with respect to each other, this would mean that the process of growing and
forming a larger structure would be made more easy. A more detailed hypothesis based on this thought is introduced in section 8.2. However, it should be still validated experimentally and mathematically.

8.2 Outlook

8.2.1 Further thoughts

Some questions are left to be investigate further. They are presented here and are the result of the further thinking about the reason why specific events happen. However, they still need to be experimentally tested.

- Are the counter rotating ring vortices, displayed in figure 5.6 and found by Dabari and Gharib,\textsuperscript{41} also present at lower Reynolds numbers, where their core is largely expanded by viscosity?

- Do these counter rotating ring vortices merge at the back of the main ring and does this clarify the stepwise decay of circulation and propagation speed at high turbulent conditions, as well as the gradually decay for laminar conditions displayed in figure 6.3, measured by Weigand and Gharib\textsuperscript{46}?

- Does the vortex bubble displayed in bright yellow in the last sub-plot of figure 6.7(a) (page 60) repel the counter rotating vortices away from the enclosed iso-velocity volume, where they form a slip layer as seen in the smoke visualisation in figure 5.8(a)\textsuperscript{47} performed by Head and Bandyopadhyay\textsuperscript{31}?

- Is the entrainment layer on top of a bulge stabilising it when looking along the bulge, from front to back?

- Are entrainment vortices entering at the back of the vortex bubble, where they merge to grow waves on the main vortex ring, often referred to as Widnall instability observed by Didden\textsuperscript{56}?

If these Questions will be answered positively, it will shed light to the question why ring vortices decay in a star form. Furthermore, it will provide information on how the energy of the small-scale entrainment vortices is providing the stability for their large-scaled bulges to form even bigger turbulent structures.

Finally, figure 8.1 provides an artist impression of an hypothesis, that still needs to be further tested, on how entrainment vortices are formed in front of a turbulent ring vortex. Moreover, on how they become stretched over the vortex bubble and how they are compressed toward the axis behind the ring over which the ring is propagating. The red ring vortex has an opposite orientation with respect to the green entrainment vortices that eventually are pulled into the vortex bubble of the red vortex, where they will merge to form wavy patterns on the ring. This process will iteratively increase the amplitudes on the red ring, as more entrainment
vortices enter to merge. In the limit, it will take on a star form, before it decays. Since the coupling of structures can couple their vortex bubbles, the possibility to keep out the entrainment vortices will form a slip-layer on top of them which could provide the stability they need to form even larger structures which might be the synergistic mechanism that provides the energy flow from small scales to large scales.

**Figure 8.1:** Artist impression of the decay of a turbulent ring vortex. The arrow indicates the perspective, the propagation direction of the red ring vortex is opposite.

### 8.2.2 Recommendations

Further research can be carried out to study the ring vortex with suitable camera software and all structures that are present can be captured at a higher Reynolds numbers so that smooth, 3D, vortex structures can be obtained. It is advised to redesign the insertion tank downstream of the test section to ensure a smother transition with the rest of the pipe. This will lead to an easier calibration procedure and avoids damage to the fragile calibration parts, like the calibration glass.

The mean profile of the out-of-plane velocity $<U_z>$, contains information about the configuration of the set-up. Therefore, it provides a direct feedback to the experimentalist about some specific errors that might have occurred during a measurement. This velocity profile can only be obtained after the post processing has been completed. This process can be time consuming, depending on the amount of data that is needed to let the velocity profile converge into smooth data and the processing power and storage capacity of the computer. However, checking the correctness of this profile is one of the most important procedures, which should
be performed before the experiments are continued. It will prevent that experiments are performed that contain errors, which only will be discovered at a later stage. Finally it is recommended to increase the injection velocity, $u_{inj}$, and reduce its injection time for the Reynolds numbers $\geq 15000$. 
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Appendix A

Improvements to the Flow Facility

A.1 Segmentation of the pipe

One of the modifications is the added manually controllable valve in the pipe inside the insertion tank as indicated in figure A.1(a). In this way the pipe is segmented so that a disturbance mechanism can be placed between the two valves. This makes testing of other mechanisms in the pipe flow facility more easy due to the increase in accessibility. It greatly reduces the loss of water and time. The former emptying of the entire pipe, discharge chamber and the settling chamber is made unnecessary. When the two valves are closed, the water between them can be removed within 5 minutes instead of the regular 45 minutes. After a re-instalment, the two valves only need to be reopened to, naturally, refill the pipe. This is completed within a few seconds since the water height in the pipe, discharge chamber and settling chamber is now able to stay at its original level during this procedure.

Caution should be taken that both valves are open, before the pump is reactivated.

Figure A.1: Overview of the transverse of the produced calibration grid holder.
A.2 The traverse of the calibration glass holder

Since the pipe had not been in use for four years, the traverse was missing and had to be rebuilt. This system is created by using the materials that were present at the location. This was done to minimise loss of time which was often encountered during a production process. Main focus points:

- 3-D alignments with respect to the orientation of the pipe inside of the test section.
- 3-D micro-adjustment capabilities, for the calibration glass in the test section.
- Easy of assembly and disassembly of the system, while keeping part of the structure in a fixed position.
- Easy of assembly and disassembly of the system, while keeping part of the structure in a fixed position.
- Easy of use and accessibility to the pipe, during cleaning and calibration procedures.
- Minimum material use and weight on top of the insertion tank.
- Stainless steel material to avoid corrosion, using aluminium to reduce weight.
- Effectiveness of operation.
- Minimising the volume of the system, providing space for other systems like the laser or lighting supports.

The three micro traverses are densely constructed together as an integrated system. It can easily be removed as a whole. The system is suspended under a single rail, that is adjustably over three axis and is mounted on top of the insertion tank. Although, one of the two valves is positioned inside the insertion tank, it is still possible to remove this pipe. This is done during a calibration process or the inner cleaning of the pipe at the test section. Removing the inner pipe is easy to do by loosening of its two, outermost, tightening rings. All rings on this pipe are indicated by number seven in figure A.1(a).

A.2.1 The calibration glass holder

Since the cameras are looking from two directions to the calibration glass, the field of view should be clean and as equal as possible on both sides of the calibration grid. In addition, the insertion of a calibration grid inside the test section of the pipe should be an easy and repeatable process. The recalibration procedure has to be performed each time an adjustment to the test section has been made. The former grid had a very tight fit, creating a, piston like, pressure on the glass when it was linearly translating inside the pipe. Moreover, it impinged many times on the edges of the pipe due to very small misalignments of the pipe with the insertion tank. The calibration glass was glued onto a transparent
A.2 The traverse of the calibration glass holder

cylinder, which in turn was tightly connected to a solid plastic cylinder. The transparent cylinder was made of thin, plastic, overhead-sheet material. With a soldering iron little holes were melted through the two ends of plastic sheet to create a firm and steady cylindrical shape that is capable of venting. The plastic transparent cylinder had been growing dim and slightly deformed over time. When it was used during PIV, particles would enter the inside of the cylinder. When the grid was taken out these particles would dry up to leave white spots on the inner side of the cylinder wall. These spots are difficult to remove and would only partly disappear when the cylinder was submerged back into the water. To ensure a clear field of view for both cameras during calibration procedures, it is required that the grid is submerged. This softens the glue that holds the glass at its position. As a result, it would slowly detach, even when it was gently traversed backwards. There has been made an attempt to reproduce the former construction. The result is displayed in figure A.2(b). It turned out not to be a robust system, due to the above mentioned reasons. Therefore, a new positioning mechanism for the calibration grid is designed and produced. The new holder is made of stainless steel. The cylinder that holds the grid is made shorter, and the diameter of the new calibration glass is reduced by 1 mm to a diameter of 39 mm. As a result, it is more capable to manoeuvre whenever a slight misalignment between the pipe and the insertion-tank is encountered. Furthermore, the piston effect is reduced, the air is no longer trapped inside the holder and the view onto the calibration grid is greatly enhanced. The new holder and its calibration grid is displayed in figure A.2.1.

Figure A.2: The old and renewed calibration grid holder.
A.3 The calibration glass

A.3.1 The Acrylate calibration grid

An attempt is made to create a new calibration glass from two 0.5 mm thick Acrylate material. Its calibration markers are laser engraved on one of the two plates on one side\textsuperscript{58}. It is covered by the other plate and secured by spectacle screws\textsuperscript{59}. After a few calibrations, air bubbles appear that are trapped between the two glasses. Therefore, a foam-less shower gel is injected between the two glasses. Thereafter, the two plates are pushed together to flush the trapped air out. This turned out to be a very effective low-cost method. It is difficult procedure to create a clear contrast with the laser engraved markers. The engraved, hemi-sphere, targets appear as quadrants as they form a shade. Therefore, the previous holder had to be covered with black tape in the previous measurements. This greatly reduced the reflections displayed in figure A.4(b). As a result, it increased the detection of the markers which appear in white.
A.3 The calibration glass

A.3.2 Creating the improved high-tech calibration glass

Although, it was possible to measure with the Acrylate calibration glass a more accurate and robust system is pursued. Therefore, a new calibration glass is developed. This high-tech calibration glass is designed, after which it is being produced by Louwers Glas. The drawings are modified slightly to ones that can be used to operate the machine that produces them. It now consists of two glasses of 0.5 mm thickness. The black indicated targets are printed onto one of the two glasses. The details are displayed in figure D.2. The other glass, displayed in figure D.3, is then attached onto its counterpart by a layer of glue that is activated by ultra violet (UV) light.

The accuracy of the position of the targets is in the order of $10^{-6}$ m. The attachment holes, that have to attach the glass to the screws, are being drilled out before the glass is hardened out. The new holder and its calibration glass are displayed in figure A.2.1. With this new method, obstruction of the field of view, created by the plastic cylinder that was present in front of one of the two cameras, does no longer exist. Moreover, the problem of trapped air between the two 0.5 mm thick glasses that is reflecting the light is completely solved. The field of view on both sides of the glass, the recognition of the targets and usability of the calibration procedure is therefore further improved. Finally, to ease the procedure of a calibration, the centre point of the calibration-glass has been marked by a square outline as displayed in figure D.1.

A.3.3 Improved accessibility at the discharge chamber

To enhance accessibility to the discharge chamber, the manhole at back of this section is modified. The inner diameter of the seal is thereby decreased, on the first 3 centimetres going inward when closing the seal. This was done to decrease the amount of friction that was encountered during the closing of the manhole seal after cleaning. Over the last centimetres going inward the former diameter of the sealing is maintained, to ensure a waterproof sealing. Plans are made to produce a larger opening on the top side of the discharge chamber.

A.3.4 The support of the laser, lenses and mirror

To increase the consistency of the orientation of the laser with respect to the lenses and mirror, they are all positioned onto a single, aluminium, beam. It is attached directly to the pipe support, as displayed in figure A.5(b). The support is created to position the laser next, and parallel, to the pipe. Therefore, two extensions are made of 0.5 cm thick hardened steel (blue). These are connected onto the main support of the pipe itself (orange) as displayed in figure A.5(a). Micro traverses are added to adjust the angle of the laser, as displayed in figure A.5(c). The vertical supports are tightened from below with 4 bolts, going through the steel plate directly into its structure. The lenses and mirror are also placed onto micro traverses. In this way, a better control, accessibility and overview is created.
Improvements to the Flow Facility

(a) extension of the main support for the attachment of the laser support
(b) The optics alignment: 1 laser blocker for safety, 2 mirror, 3 and 4 lenses, 5 laser.
(c) Laser supported by two micro transverses 1 and 2.

Figure A.5: Supports and alignment possibilities to increase the accurateness of a measurement.

A.3.5 The vortex generator inside the injection mechanism

(a) Side-view of the vortex generator, showing the cut out position in the middle where the flanges are attached. Flow from left to right.
(b) Top-view of details of the injection opening.

Figure A.6: The vortex generator designed by C.M. Sanders and produced by DEMO. The injection mechanism has to generate a large-scale structure that should interact with the smaller scales that are naturally contained within the flow. The vortex generator is contained within the injection chamber. The vortex generator is replacing the previously installed porous wall inside the injection chamber. The vortex generator is displayed in figure A.6.
The main focus points of the design of the vortex generator are:

- Re-usability of the injection chamber as it was used by Cas van Doorne\textsuperscript{18}.
- Inner diameter of the injection mechanism equals the inner diameter of the pipe.
- Minimal disturbance to the flow without injection.
- Water proof mechanism.
- Hydrodynamic effects, roll-up.
- Weight, minimising the bending load on the pipe, PVC.
- Corroding free material, PVC.
- Homogeneous injection.
- A accurate fit into the injection chamber.
Appendix B

Restoring the Flow Facility

B.1 The laser chamber

To obtain a clear, clean and safe working environment the old area of the facility needed to be emptied out, cleaned and rebuilt. All unnecessary units are removed from the measurement area. The area is stripped of all its cluttered cables and dust. All cables are checked on their functionality before they are sorted. Thereafter, the floor of the room is cleaned thoroughly, to avoid sensitive aperture from becoming damaged by dirt. Furthermore, the area is closed and made laser proof. A replaceable wall is put, where before would be the open side of the room. This is done to prevent laser light from escaping the room and people from randomly entering it. Lever-switches are placed above the doors. These will automatically switch off the laser whenever the door is opened during a measurement. The laser is always ending at a plate, so that reflection of the light into a person’s eyes or other parts of the body is prevented. Background noise, sensed by the cameras, is reduced by covering all areas where natural light could enter the room. The switch of the main light and the laser-on warning lights is reinstalled in the centre of the room. They can be easily found and controlled in this manner. The work environment is installed at this place as well. Computer controlled devices can therefore be more directly connected.

B.2 Opening the pipe

Since the fluid inside the pipe of the flow facility had been at rest for four years, the pipe needed some cleaning and restoring before could be operated. At some pipe sections outside the laser room the insulation foam was missing. As a result, algae had been growing inside the pipe that had to be removed. In figure B.1(a) and B.1(b) it is visualised how the side-flanges have to be loosened by removing the bolts. During the opening procedure, two half-pipes are put between one of the side-flanges and the "cover-cylinder". This cylinder over-covers the...
(a) Closed assembly of the interconnection of the pipes with: 1 cover cylinder, 2 tightening disc, 3 tightening bolt, 4 algae in the pipe, 5 insulation cover, 6 protection cover, 7 alignment pillar.

(b) Disensambled pipe interconnection with: 1 eind part of a pipe, 2 sealing o-ring.

(c) Opened positioning pillars, 1 reservoirs.

(d) Generated torque (4).

(e) Reassambled pipe facility with added gray cover of insulation foam.

Figure B.1: Stages and attention points during the disassembling of the pipe.

two pipe ends. The result is displayed in figure B.1(d) by numbers 1 and 2. Thereafter, the bolts are reused and tightened to shift the covering-flange to one side. This is opening the pipe and one of the two ends of the pipe will have to be supported since it is now suspended, and experiencing a load under its own weight. This moment is displayed in figure B.1(b). During the removal of a pipe segment two small containers are placed at its outer locations to capture the surprisingly large amount of remnant-water (figure B.1(c)). When the segment is out, the cleaning starts. One could see that the algae were only growing locally, where the sunlight had been able to illuminate the pipe. To prevent the algae from spreading through the entire system, the pipes that surround that location are both taken out to clean. With a white cloth the inside of the pipe is cleaned. In this way, a quick visual check, of cleanliness of the cloth, is easily done before its use. The cloth is pushed through the pipe and removes the algae towards the location of its source. During the first swipe, most of the algae was removed. This process was repeated two times more. Finally, the insulating cover was put over the pipe, the pipe sections reconnected and the insulating cover repositioned. Opening and closing of the pipe needs careful attention. When the covering-flange is not shifted parallel to the pipe it will create a couple moment perpendicular to the pipe (going out of the plane) as indicated in red in figure B.1(d). In that case, the pipe will crack. Therefore, turning of the bolts is done in an alternating way.

The valves:

Before the pipe is switched on, it is first filled with water and then left for one day and night to see if any leakage would occur. At the discharge chamber there is a maximum water level mark to keep the tank from leaking. Only when it is filled even further, its lower plate will start to bend under the weight of the water and would start leaking. In the early morning, the following day, the level of the discharge chamber suddenly appeared low. Luckily the only leak that was remaining turned out to be the manually operating valve to the suer that was mall functioning. Although, leakage of water trough the valve could not be heard it was carefully checked by opening the ring that is located behind the valve. Since the valve itself
was closed the water should maintain inside the system. Nevertheless, it clearly leaked some water. Therefore, it was taken out, checked, cleaned and placed back. After its placement the leaking of water had stopped.

**Pressure holes and water-hoses:**
During the restoration of the facility all hoses were found to be fouled by algae. Inevitably, all hoses had to be measured and replaced with new ones. During the replacement, all attach nozzles of the hoses are checked and cleaned as well. Disconnected nozzles are glued back into their position on the pipe to ensure a waterproof composition.

### B.3 Changing the test section

The water inside the optical box, that is surrounding the pipe at the test section, was blurred with particles of all kind. Furthermore, there were many planes that would reflect the laser light. Therefore, the original, in complexity reduced, test section was reinstalled. The grease that was used to make the section waterproof had become old and part of it became solved in the water of the test section. Opening of the test section has to be done in a careful way. First and foremost, the section is supported after which the crews are loosened. At that instant, eight parts simultaneously will come loose, so coordinating the work is of crucial importance to prevent any parts from breaking. Then, it was discovered that the glass tube inside the test section was missing a chip. As a consequence, PIV particles could enter the area outside the pipe. These would then circulate through the field of view of the cameras, in the water of the optical box, during the measurements. Moreover, the chip could generate an unwanted vortex structure. To prevent this, a new pipe section is put into place. In addition, the venting tubes that are filled with grease are cleaned out and checked for functionality. Finally, the sealing rubbers are renewed before everything is closed.

![Figure B.2: The change of test section to obtain better optical properties](image-url)

(a) Installed test section with adjustable prisms containing many reflective planes.  
(b) Found chip in the pipe, after disassembly.  
(c) The newly installed test section showing less possibilities to reflect the laser light.
Thereafter, the glass tube was closed in a waterproof manner, containing little pressure on
the pipe, but still closing the test section box. Running the pipe without water in the test
section box indicated that the pipe was well sealed. The main result is shown in figure B.2(A).

Running the pipe:
The manual of the frequency regulator is read to ensure that the nominal value of the motor
is not exceeded. Shortly afterwards, it was found that the frequency regulator had been put
to remote. This means that the nominal values could not have been changed since the last
activation of the pump. This is due to the fact that the remote frequency regulator is not
capable of modifying nominal values of the local frequency regulator. After the repairing and
cleaning, the pipe is activated by making use of the remote control. No leakage was found.

B.4 Solving the laser cooler leakage

The day after the arrival of the repaired laser from England an unfortunate problem occurred.
Its laser cooling system was loosing water. This leak was traced back and repaired. The silicon
rubber sealing-ring, that is positioned around the sealing screw, had been the source. Both
sides were covered in grease while its inner diameter was designed to large. During tightening
of the sealing-screw the silicon inner diameter would stretch since it is positioned over a section
of the screw that has a conical shape, after which it goes over into the helix of the screw.
Moreover, its inner diameter would stretch when it is put under pressure during the tightening
of the sealing-screw as it is pulled to the backside of the cone-shaped screw. Therefore, it
will slip over to reach the helix that had cut out a chip from where it started leaking water,
as can be seen from figure B.3(a). The laser cooler unit will only open a short distance as
indicated in figure B.3(c). It is connected on the inside to a harmonic cover, displayed in
figure B.3(b). This harmonic cover needs to be detached from its backside to gain access to
the water reservoir. There, the sealing screw is removed and the silicon sealing ring is taken
out and investigated. Te problem is solved by producing a new sealing ring that consists of
the same material and thickness. Its inner diameter is made smaller that that of the screw

Figure B.3: The laser power cooling system
so that it would obtain the same diameter as the screw, when it is put under pressure, but would not slip over the helix of the screw. Furthermore, only one side of the silicon rubber sealing is covered with grease. As a result, the other side of the ring creates friction that keeps the rubber from moving. After this modification, the leakage was gone and the laser-cooling system is now performing well again.
Appendix C

Derivations

C.1 The expression for Q in Matlab

C.2 Reynolds conditions

\[ f + g = \bar{f} + \bar{g} \quad (C.1) \]
\[ \alpha f = \alpha \bar{f} \quad (C.2) \]
\[ \frac{\partial f}{\partial s} = \frac{\partial \bar{f}}{\partial s} \quad (C.3) \]
\[ fg = \bar{f} \bar{g} \quad (C.4) \]

Where \( f \) and \( g \) are functions and \( \alpha \) a multiplicative constant.

C.3 Derivation of the Darcy friction factor

\[ (P + \frac{dP}{dx} \Delta x - P)\pi R^2 = 2\pi R \tau \Delta x \Rightarrow \frac{\Delta P}{\Delta x} = \frac{2\tau}{R} \Rightarrow \frac{\Delta P}{\Delta x} = \frac{4\tau}{D} \quad (C.5) \]

When substituting

\[ \tau = \frac{f_D}{8} \rho U^2 \Rightarrow \frac{\Delta P}{dx} = f_D \frac{\rho U^2}{2} \frac{1}{D} \quad (C.6) \]

When substituting \( L \) for \( \Delta x \)

\[ \Rightarrow f_D = \frac{2\Delta P}{L} D \frac{1}{\rho V^2} \quad (C.7) \]

Or:

\[ \Rightarrow f_D = \frac{2D}{L} \frac{1}{\rho V^2} \Delta P \quad (C.8) \]
D.1 Design drawings and the dye supply mechanism

The design of the calibration glasses can be found in figure D.1, D.2 and D.2 which are redrawn for the production by the company Louwers Glas. The calibration glass is made out of Quartz glass. Lithography is applied to create the black markers after which the two glasses are melted together with glue that is activated by UV light.

The ink supply mechanism becomes clear when following the indicated numbers in figure D.4. Going from 1-9, the ink moves from the reservoir to a splitter at location 3, which ensures both sides can be fed. However since the piston is more to the right the splitter at location 3 experiences suction from the left. Therefore check-valve 0' is closed. A similar process takes place at location 5 where check-valve 0 is closed. From location 5 the ink goes to location 7 where it is split to fill both inner left sides of the pistons at locations 9. At the same time the following process is taking place. Going from 1' to 8' the ink is leaving both right sides of the pistons at location 1'. The splitter at location 3' is now combining the ink of both pistons. When the ink arrives at splitter 5' check-valve 0' is closed and check-valve 6' is open. A similar process takes place at location 7' where check-valve 0 is closed and the ink is directed into the tube indicated by 8'. Therefore the ink is now feeding the injection mechanism. Since this mechanism is symmetric the process is repeated the other way around when the piston is moving to the left. Then check-valves 0 and 0' will open and check-valve 4 and 6' will close. This ensures that injection and absorption of ink can be done simultaneously, completely isolated. At a later stage where the SPIV measurements are done the feeding hose indicated by number 2 is directly connected to the discharge chamber via a longer hose, which has a larger diameter to reduce pressure drop.
Figure D.1: Details of the centre of the calibration glass showing that the centre is marked to increase the recognition of the centre of the glass during a calibration procedure.
Figure D.2: Detailed information of the attachment positions of the glass note the difference in each position of these points.
Figure D.3: The complementary other half of the calibration glass again note the difference in each position of the attachment points.
Figure D.4: The ink supply mechanism to the injection chamber