# APPENDIX A

## A. Related literature on continuous casting

As explained in the text, these references are shown only for the sake of completeness, as this dissertation is part of an ongoing continuous casting CFD modelling exercise at the University of Pretoria in collaboration with THRIP partners[1] from the industry.

Firstly, the Tundish references diagram is shown to show the resemblances to the classification of typical literature.

### A.1 Tundish diagram

[1] THRIP: Technology and Human Resources for Industry Programme of South Africa; a partnership programme funded by the Department of Trade and Industry (DTI) and managed by the National Research Foundation (NRF)
Industry THRIP partners to University of Pretoria, Department Mechanical and Aeronautical Engineering, cfd-labs : Columbus Stainless (main partner), LTM technologies and Foseco

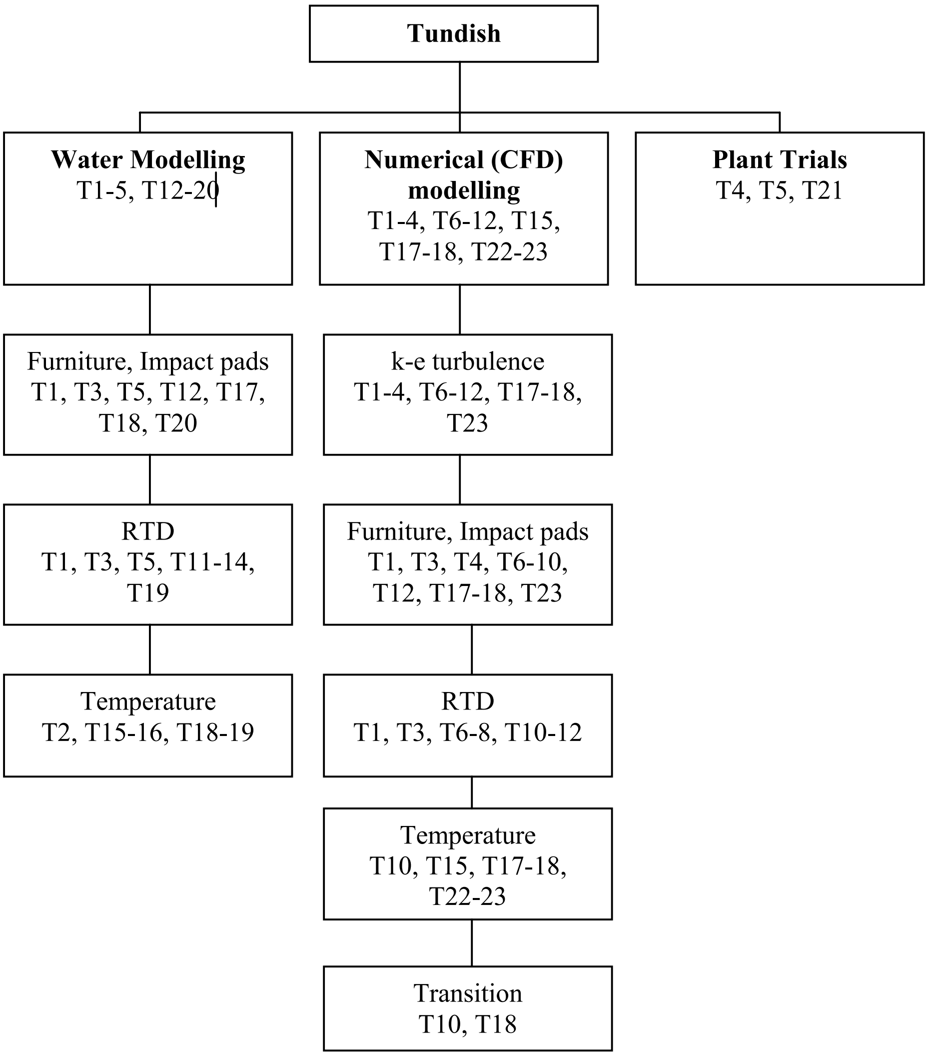



Diagram A.1: Tundish classification of literature

## A.2 Tundish (T), Inclusions (I) and Ladle (L) references

### T: Tundish

1) R. D. Morales, J. deJ Barreto, S. Lopez-Ramirez and J. Palafox-Ramos, Melt Flow Control in a multistrand tundish using a turbulence inhibitor, *Metall. Trans. B.*, 31B (2000), 1505.
2) D. Y. Sheng and L. Jonsson, Two-Fluid Simulation on the Mixed Convection Flow Pattern in a Nonisothermal Water Model of Continuous Casting Tundish, *Metall. Trans. B.*, 31B (2000), 867.
3) S. Lopez-Ramirez, J. deJ Barreto, J. Palafox-Ramos, R. D. Morales and D. Zacharias, Modeling Study of the Influence of Turbulence Inhibitors on the

Molten Steel Flow, Tracer Dispersion, and Inclusion Trajectories in Tundishes, *Metall. Trans. B.*, 32B (2001), 615.

4) L. Zhang, S. Taniguchi and K. Cai, Fluid Flow and Inclusion Removal in Continuous Casting Tundish, *Metall. Trans. B.*, 31B (2000), 253.
5) M.A. Schueren, J. Schade and R. J. Komanecky, Quality and Productivity Improvements with a Revised Tundish Flow System at AK Steel's Middletown Works, unknown. 2001 and 2002 ISS award winner.
6) Craig, K.J., de Kock, D.J., Makgata, K.W. & de Wet, G.J. Design Optimization of a Single-Strand Continuous Caster Tundish Using RTD Data, *ISIJ International*, Vol.41, No.10, pp.1194-1200, 2001.
7) De Kock, D.J., Craig, K.J. & Pretorius, C.A., Mathematical Maximisation of the Minimum Residence Time for a Two-Strand Continuous Caster, accepted, *Ironmaking and Steelmaking*, Dec. 2002.
8) De Kock, D.J., Craig, K.J. & Pretorius, C.A., Mathematical Maximisation of the Minimum Residence Time for a Two-Strand Continuous Caster, 4$^{th}$ European Continuous Casting Conference, 14-16 October 2002, Birmingham, UK.
9) S. Joo, J.W. Han and R.I.L. Guthrie, Inclusion Behavior and Heat_transfer Phenomena in Steelmaking Tundish Operations: Part III. Applications – Computational Approach to Tundish Design, *Metall. Trans. B.*, 24B (1993), 779.
10) C. Damle and Y. Sahai, Modeling of Grade Change Operations During Continuous Casting of Steel – Mixing in the Tundish, Transactions of the ISS, June 1995, 49.
11) P.K. Jha and S.K. Dash, Effect of Outlet Positions and Various Turbulence Models on Mixing in a Single and Multi Strand Tundish, *International Journal of Numerical Methods for Heat and Fluid Flow*, 12(5) (2002), 560.
12) S. Joo and R.I.L. Guthrie, Inclusion Behavior and Heat_transfer Phenomena in Steelmaking Tundish Operations: Part I. Aqueous Modelling, *Metall. Trans. B.*, 24B (1993), 755.
13) Y. Sahai and T. Emi, Melt Flow Characterization in Continuous Casting Tundishes, *ISIJ International*, 36(6) (1996), 667.
14) Y. Sahai and R.Ahuja, Fluid Flow and Mixing of Melt in Steelmaking Tundishes, *Ironmaking and Steelmaking*, 13(5) (1986), 241.
15) D.Y. Sheng, C.S. Kim, J.K. Yoon and T.C. Hsiao, Water Model Study on Convection Pattern of Molten Steel Flow in Continuous Casting Tundish, *ISIJ International*, 38(8) (1998), 843.
16) A.K. Sinha and A. Vassilicos, Physical Modelling of Thermal Effects on Steel Flow and Mixing in Tundish, *Ironmaking and Steelmaking*, 25(5) (1998), 387.
17) R. D. Morales, S Lopez-Ramirez, J. Palafox-Ramos and D. Zacharias, Numerical and Modeling Analysis of Fluid Flow and Heat Transfer of Liquid Steel in a Tundish with Different Flow Control Devices, *ISIJ International*, 39(5) (1999), 455.
18) D. Y. Sheng and L. Jonsson, Investigation of Transient Fluid Flow and Heat Transfer in a Continuous Casting Tundish by Numerical Analysis Verified with Nonisothermal Water Model Experiments, *Metall. Trans. B.*, 30B (1999), 979.
19) M.L. Lowry and Y. Sahai, Thermal Effects on the Flow of Liquid Steel in Continuous Casting Tundishes, Transactions of the ISS, March 1992, 81.
20) R.W. Crowley, G.D. Lawson and B.R. Jardine, Cleanliness Improvements Using a Turbulence-Suppressing Tundish Impact Pad, 1995 Steelmaking Conference Proceedings, 629.

21) H. Tanaka, R. Nishihara, I. Kitagawa and R. Tsujina, Quantitative Analysis of Contamination of Molten Steel in Tundish, *ISIJ International*, 33(12) (1993), 1238.
22) S. Joo, J.W. Han and R.I.L. Guthrie, Inclusion Behavior and Heat_transfer Phenomena in Steelmaking Tundish Operations: Part II. Mathematical Model fo Liquid Steel in Tundishes, *Metall. Trans. B.*, 24B (1993), 767.
23) Y. Miki and B.G. Thomas. Modeling of Inclusion Removal in a Tundish, *Metall. Trans. B.*, 30B (1999), 639.

## I: Inclusions and Steel Cleanliness

1) L. Shang and B.G. Thomas, Alumina Inclusion Behavior during Steel Deoxidation, *7th European Electric Steelmaking Conference*, Venice, Italy, May 26-29, 2002.
2) L. Zhang and B.G. Thomas, State of the Art in Evaluation and Control of Steel Cleanliness, *ISIJ International*, 43(3) (2003), 271.
3) L. Zhang, W. Pluschkell, B.G. Thomas, Nucleation and Growth of Alumina Inclusions during Steel Deoxidation, *85th Steelmaking Conference*, (Mar. 10-13, 2002, Nachville, TN), Vol.85, ISS, Warrendale, PA, 2002, 463.

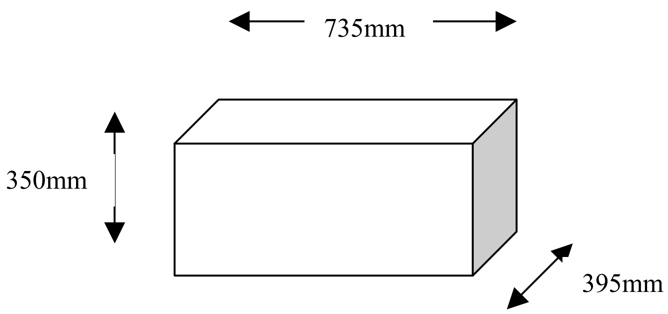
## L: Ladle

1) L. Zhang, Mathematical Simulation of Fluid Flow in Gas-Stirred Liquid Systems, *Modelling Simul. Mater. Sci. Eng.*, 8 (2000), 463.
2) B. Barber, G. Watson and L. Bowden, Optimum Ladle Design for Heat Retention during Continuous Casting, *Ironmaking and Steelmaking*, 21(2) (1994), 150.

# APPENDIX B

## B. Detail drawings of bottom tank (2.5mm sheets)

The basic dimensions of the rectangular bottom tank are:




The bottom tank is designed from 2.5mm stainless steel, and consists of 7 pieces of sheet metal welded together using a TIG welding process.

7 pieces of sheet metal:

- belly or base
- top with holes
- side (left)
- side (right – with exit hole)
- support and baffle (right)
- support and baffle (identical for middle and left)

The detail drawings (extracted from Solid Edge [60]) are shown in Figures B.1 to B.6. It is interesting to note that the tank sheets are drawn in the folded position using Solid Edge, but can be automatically unfolded using Solid Edge to generate drawings of the flat sheets. The folded open sections are preferred by the laser cutting industry for obvious reasons.

Additional stainless steel sections needed to be welded onto the top section after the tank has been welded together. The function of these protruding sections is to facilitate sealing of the wide and narrow mould walls during operation of the water model.

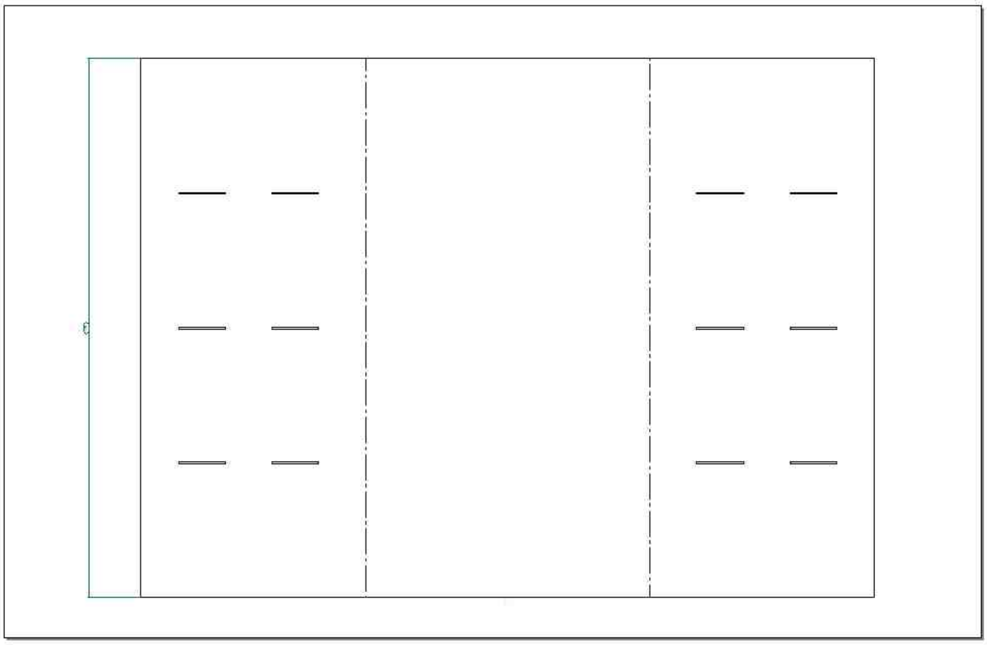


Figure B.1: Detail folded open drawing extracted from Solid Edge: Belly or base

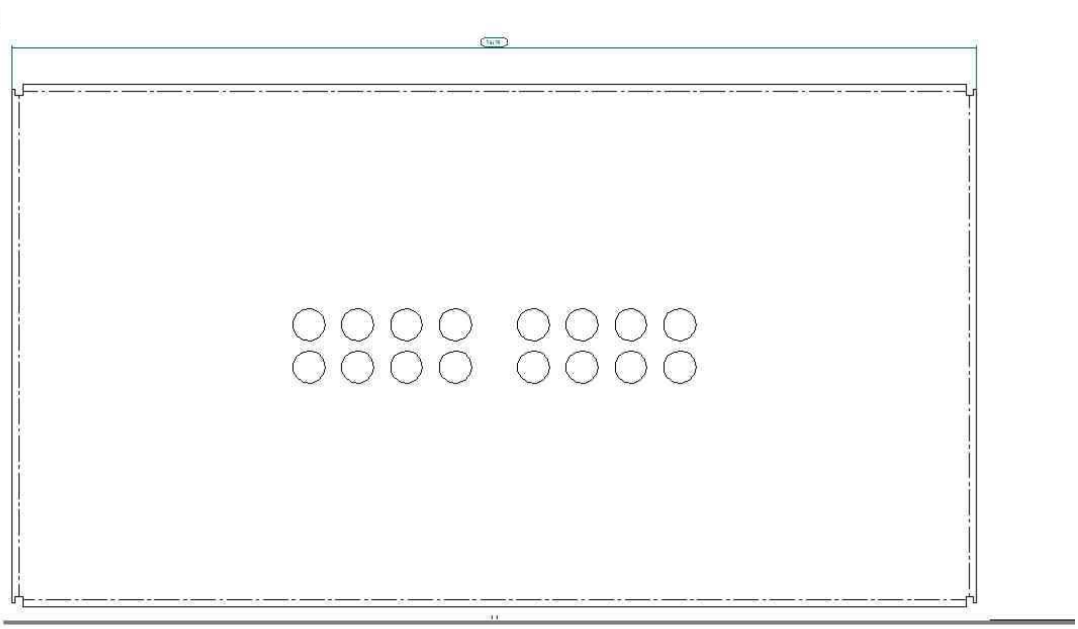


Figure B.2: Detail folded open drawing extracted from Solid Edge: Top

Figure B.3: Detail folded open drawing extracted from Solid Edge: Side, left

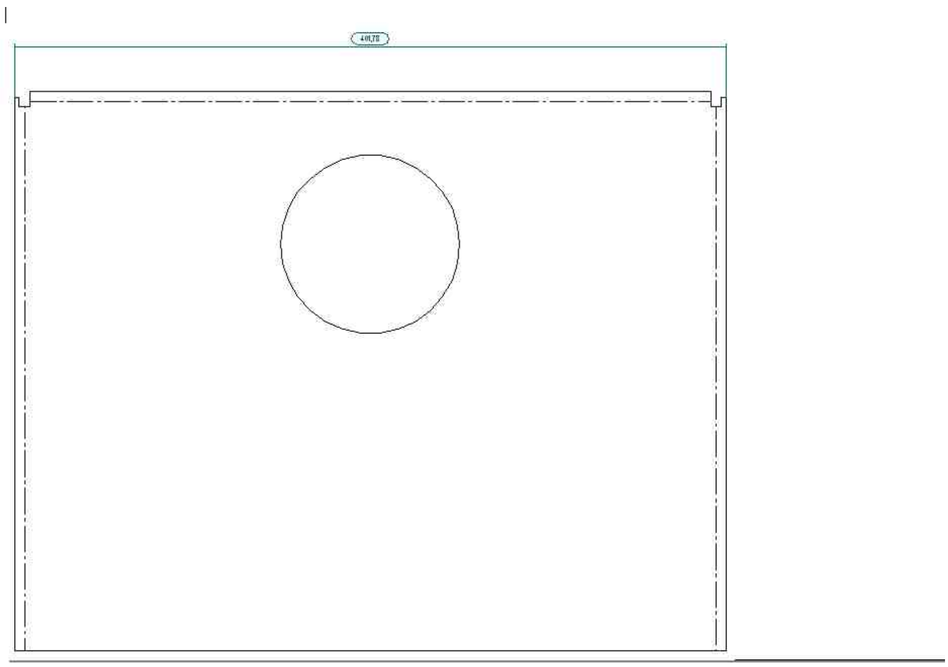


Figure B.4: Detail folded open drawing extracted from Solid Edge: Side, right

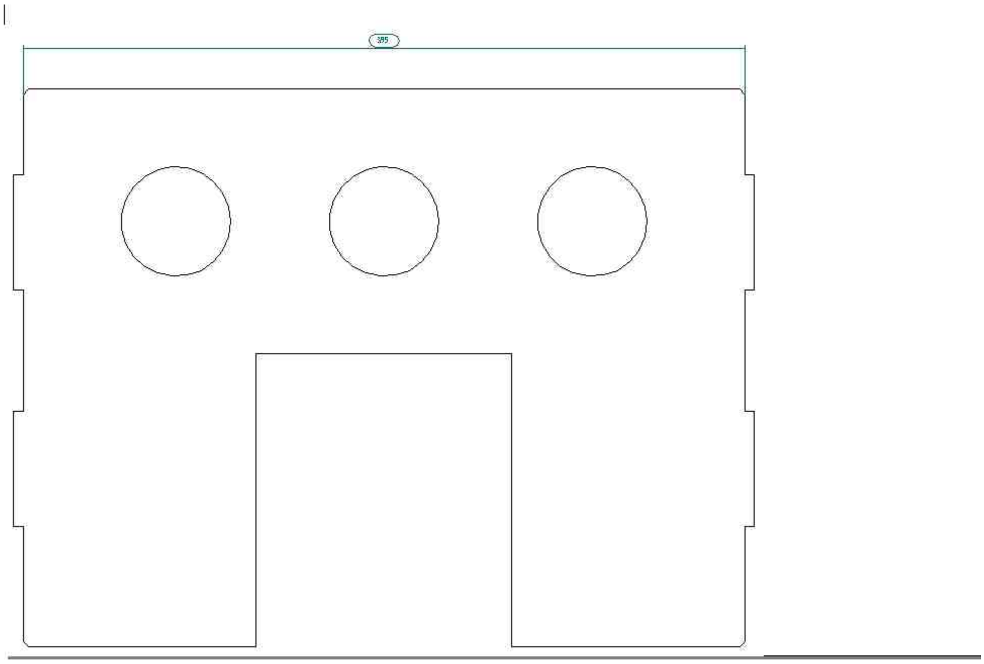



Figure B.5: Detail folded open drawing extracted from Solid Edge: Support and baffle, right

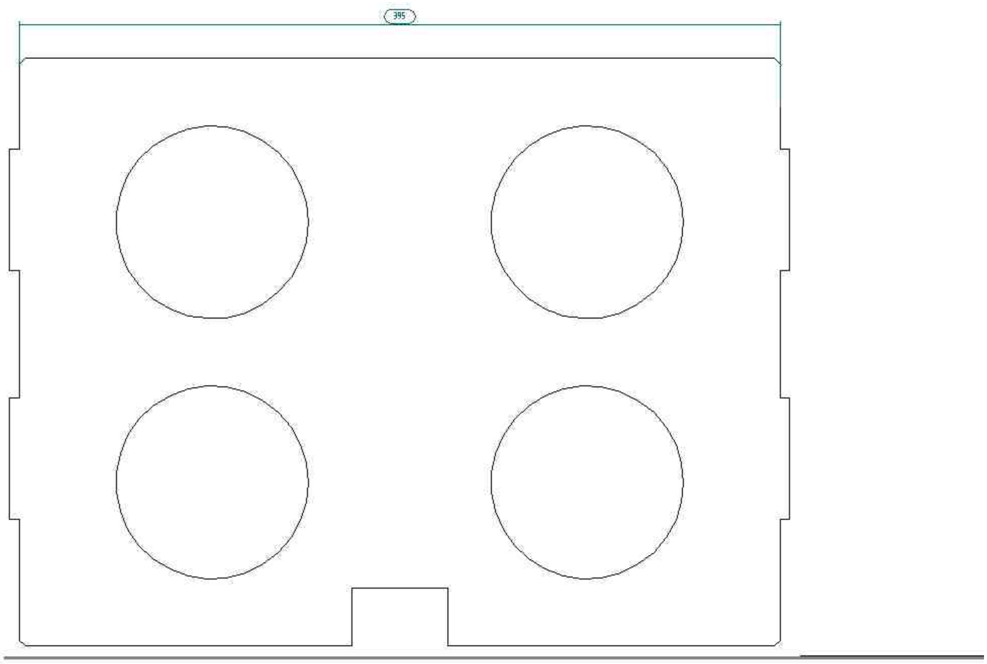



Figure B.6: Detail folded open drawing extracted from Solid Edge: Support and baffle, middle and left

# APPENDIX C

## C. Chosen steel sections for frame / structure and accompanying drawings

### C.1 Chosen steel sections for frame/structure

The frame was designed to accommodate the following loads:

- mass of the water inside the perspex mould
- mass of the (full with water) top cylindrical tank
- forces due to the water pressure (≈ $\rho g h$) inside the perspex mould

Table C.1: Steel sections for water model frame

| Member description | Subjected to: | Steel section |
|---|---|---|
| Legs (x4) | Axial load (as a column member), as well as bending from the opposing bolt forces) | Angle section, 50 x 50 (cross sectional) x 6 mm (thickness) |
| Feet (x2) | Bending at bolted sections | Angle section, 50 x 50 x 6 mm |
| Separator (horizontal) sections (x4) | Bending due to opposing bolt forces and possible frame movement | Square tubing section, 75 x 75 x 3 mm |
| Hanging members (x4) | Bending due to opposing bolt forces. | Square tubing, 75 x 75 x 3 mm |
| Perspex supporting beams (x4 for both sides) | Bending due to hydrostatic pressure | Angle section, 30 x 30 x 3 mm |
| Supporting beams for torsional stability (x8) | Axial and compressive loads | Angle section, 30 x 30 x 3 mm |
| Support for bottom tank (x2) | Bending due to weight of filled perspex mould and filled bottom tank | Angle section, 50 x 50 x 6 mm |
| Support for top tank (x2) | Bending due to weight of top tank and mass of supply pipe | Angle section, 50 x 50 x 6 mm |
| Diagonal struts for stiffness | Axial and compressive loads | Angle section, 50 x 50 x 6 mm |

All the sections were chosen to exhibit a Safety Factor of at least 2 during the maximum loaded cases.

## C.2 <u>Detail hand drawings of frame</u>

Figures C.1 to C.3 depict the front, side and top view of the assembled frame respectively.

Figure C.4 shows more detail of the four (identical) hanging sections.

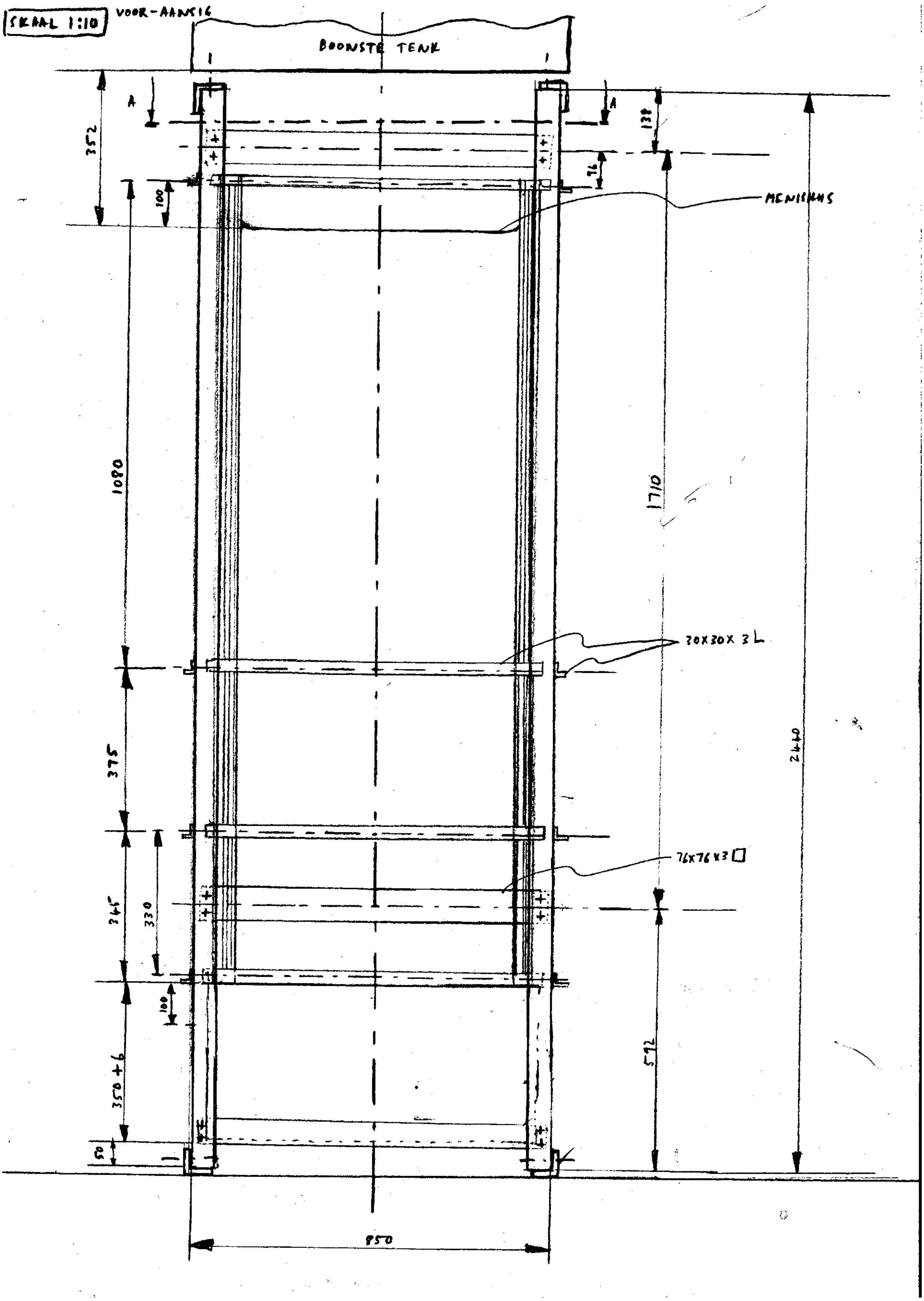



Figure C.1: Water model frame, front view: Detail hand drawing

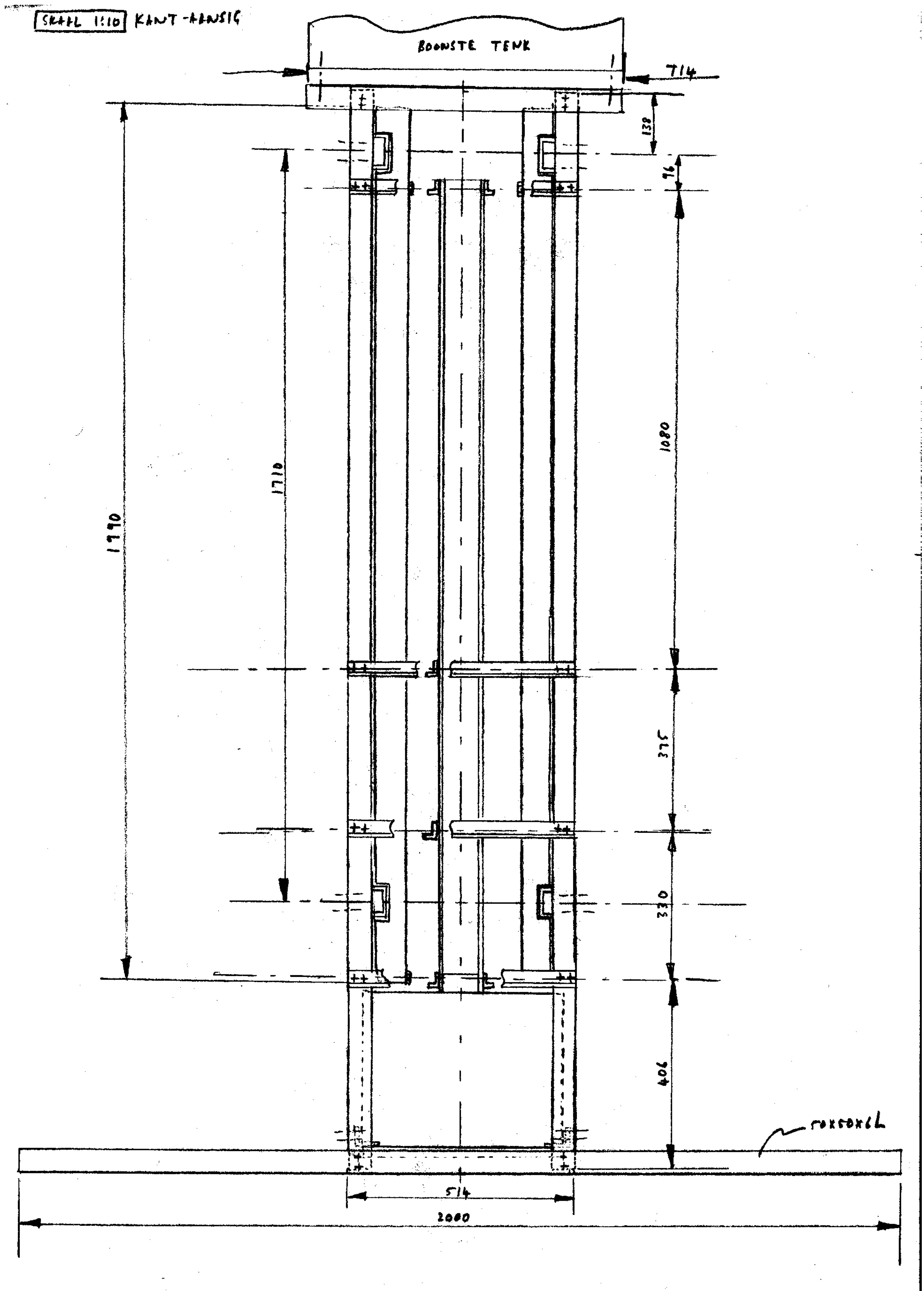



Figure C.2: Water model frame, side view: Detail hand drawing

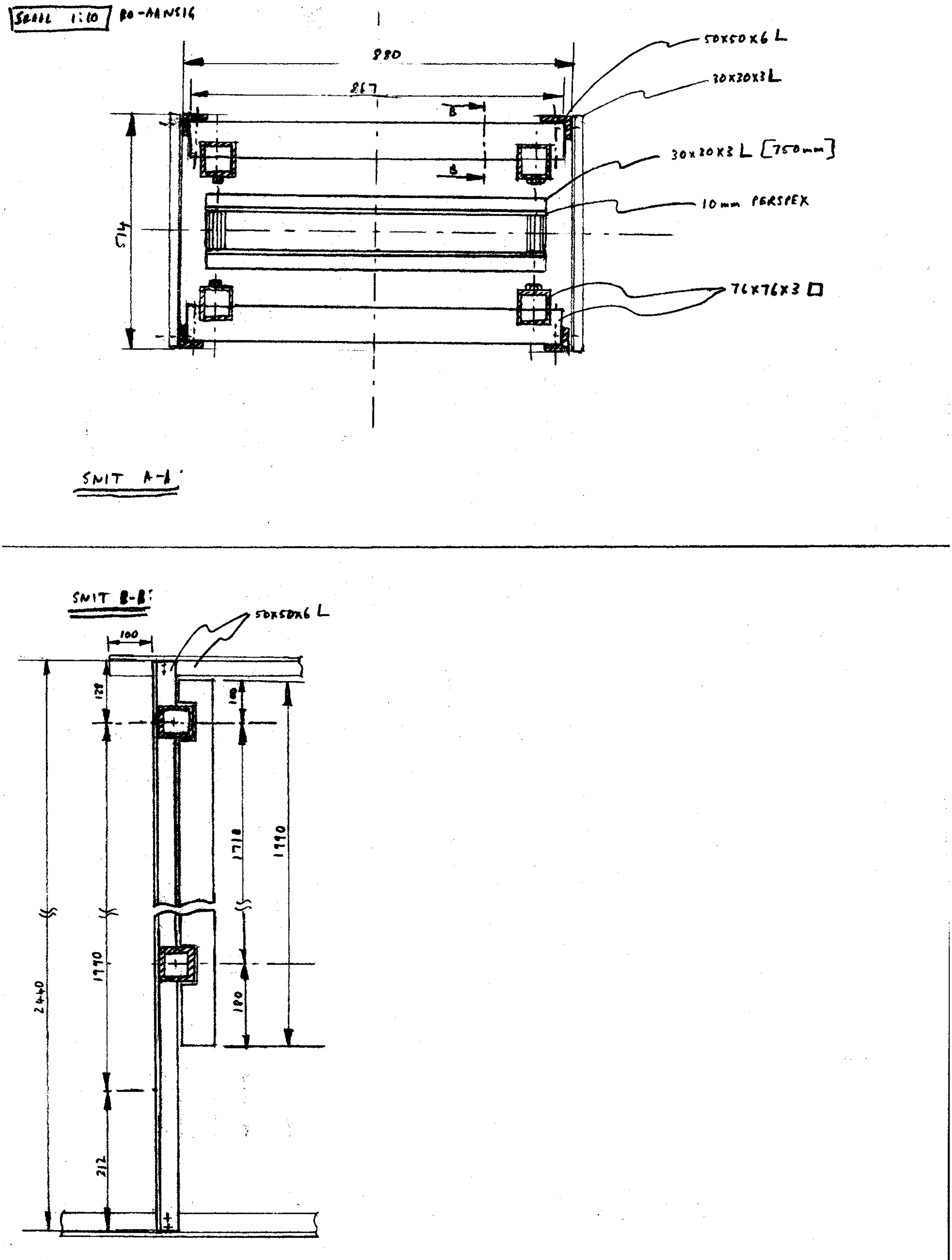



Figure C.3: Water model frame, top view and detail: Detail hand drawing

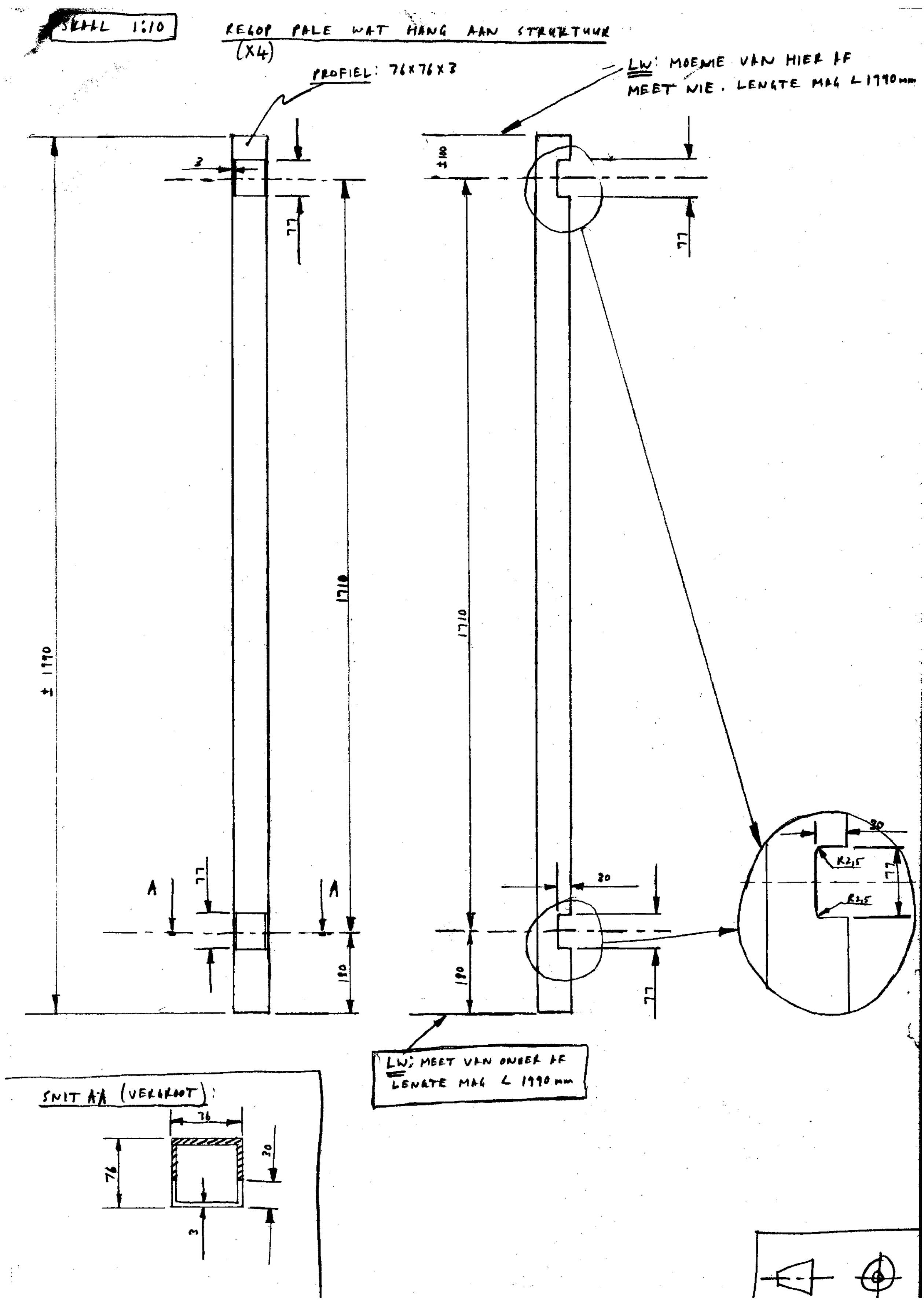



Figure C.4: Water model frame: detail of hanging sections: Detail hand drawing

# APPENDIX D

## D. Aluminium 40% scaled SEN: hand drawings for manufacture

Some detail drawings for the Aluminium SEN are presented in Figures D.1 to D.3 below, and the following information will be presented:

- Assembly drawing: full section
- Assembly drawing: side view
- Auxiliary sections and views

Figure D.4 is the detail drawing of the mandrel required to manufacture all three parts of the SEN. The mandrel is the positive geometry of the inside of the SEN, and will be manufactured from copper to be used during the spark erosion technique.

Figure D.5 is a dimensional assembly drawing of the 40% scaled stopper and SEN upper part.

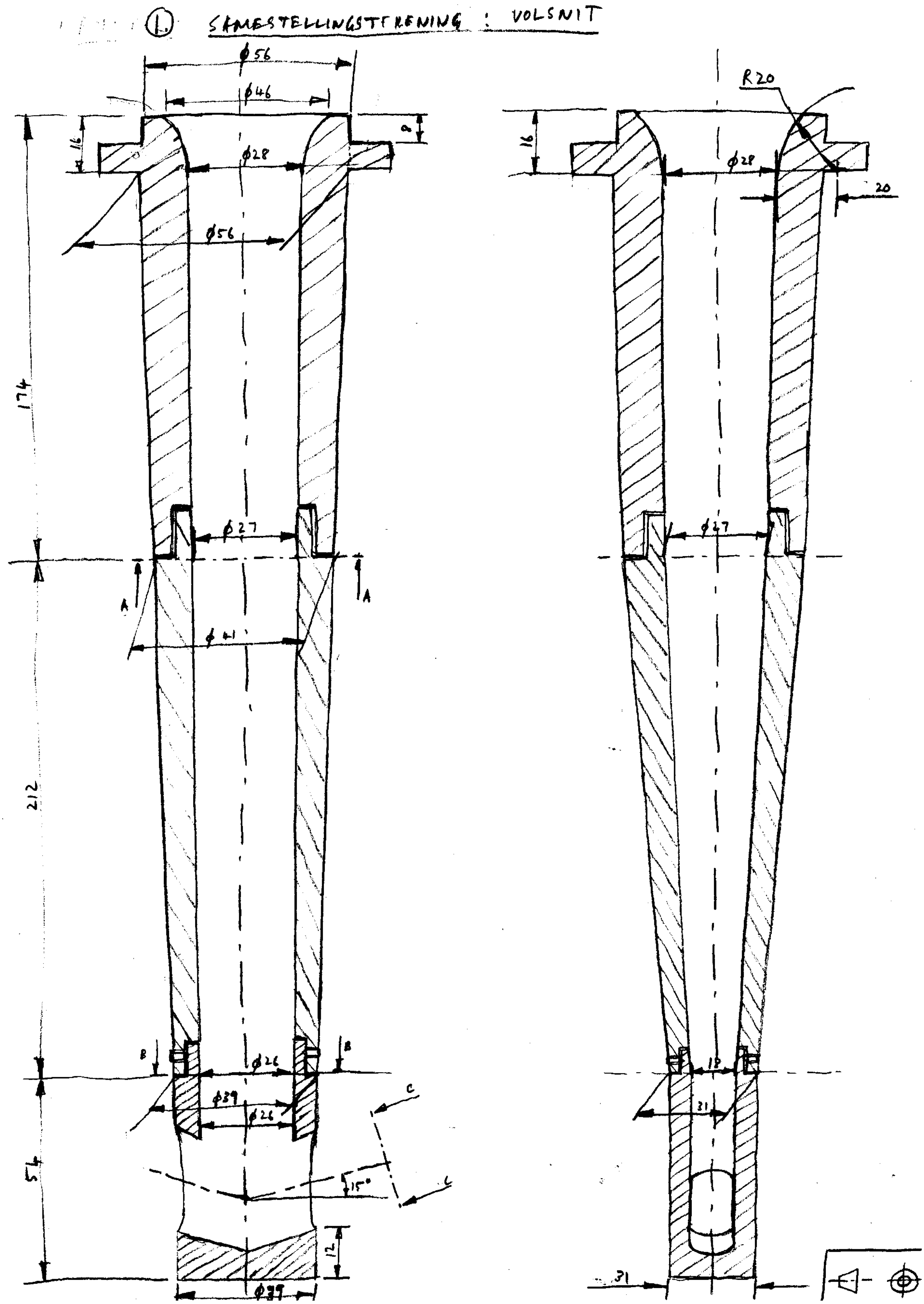



Figure D.1: Aluminium SEN: Assembly drawing: full section

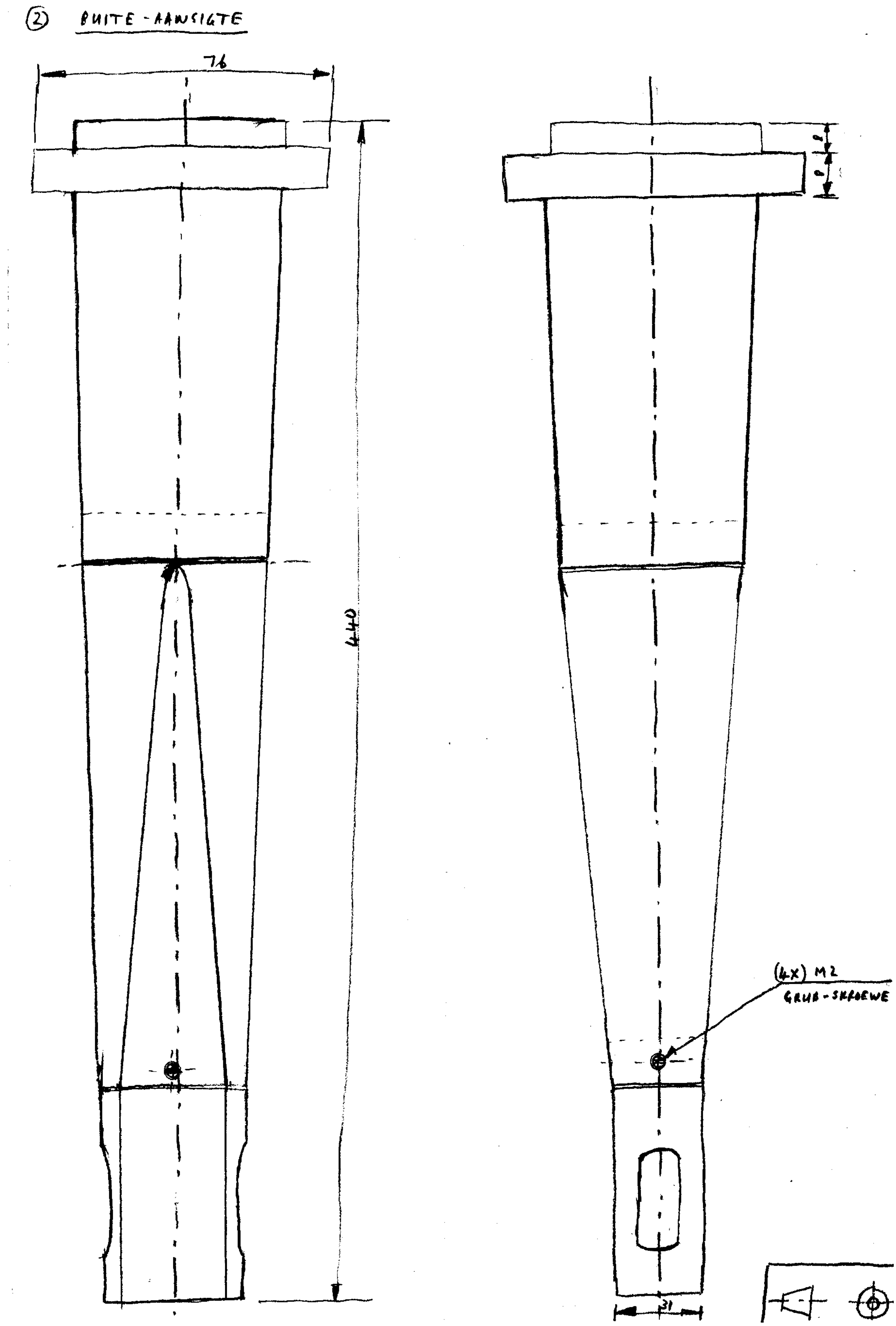
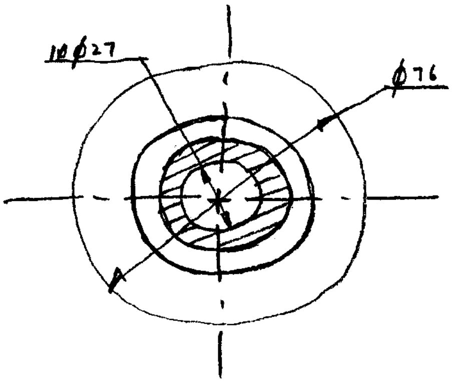


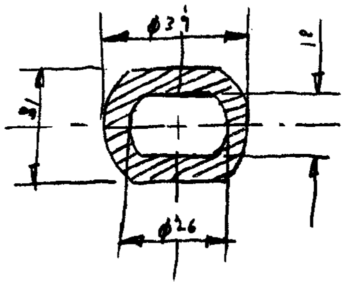

Figure D.2: Aluminium SEN: Assembly drawing: side view

③ HULPSNITTE EN -AANSIGTE

SNIT A-A:




SNIT B-B:




AANSIG C-C:

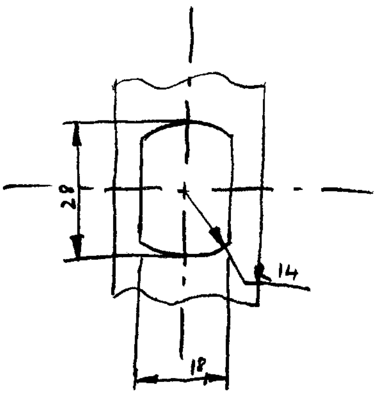



Figure D.3: Aluminium SEN: Auxiliary sections and views

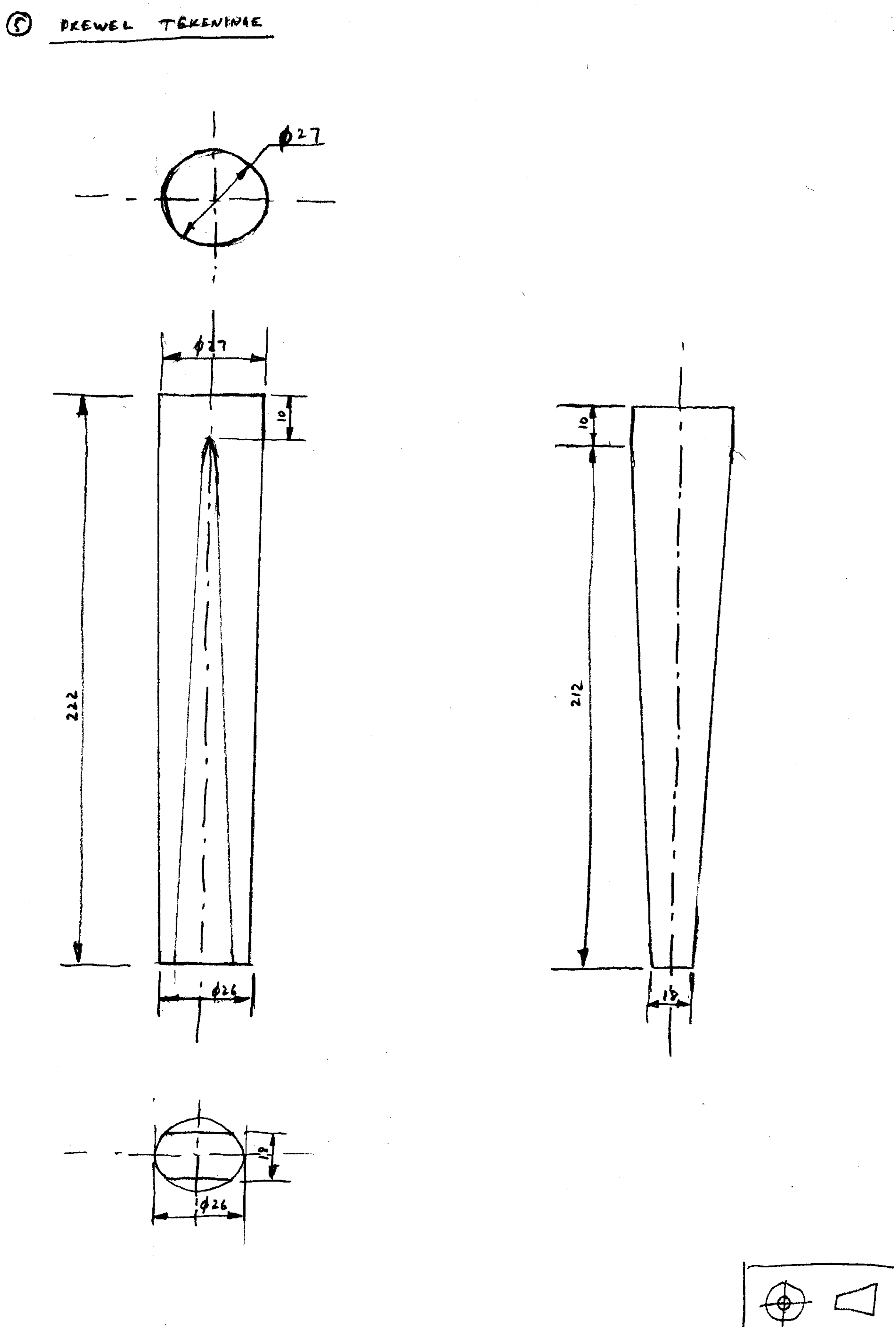



Figure D.4: Mandrel for manufacture of Aluminium SEN inside

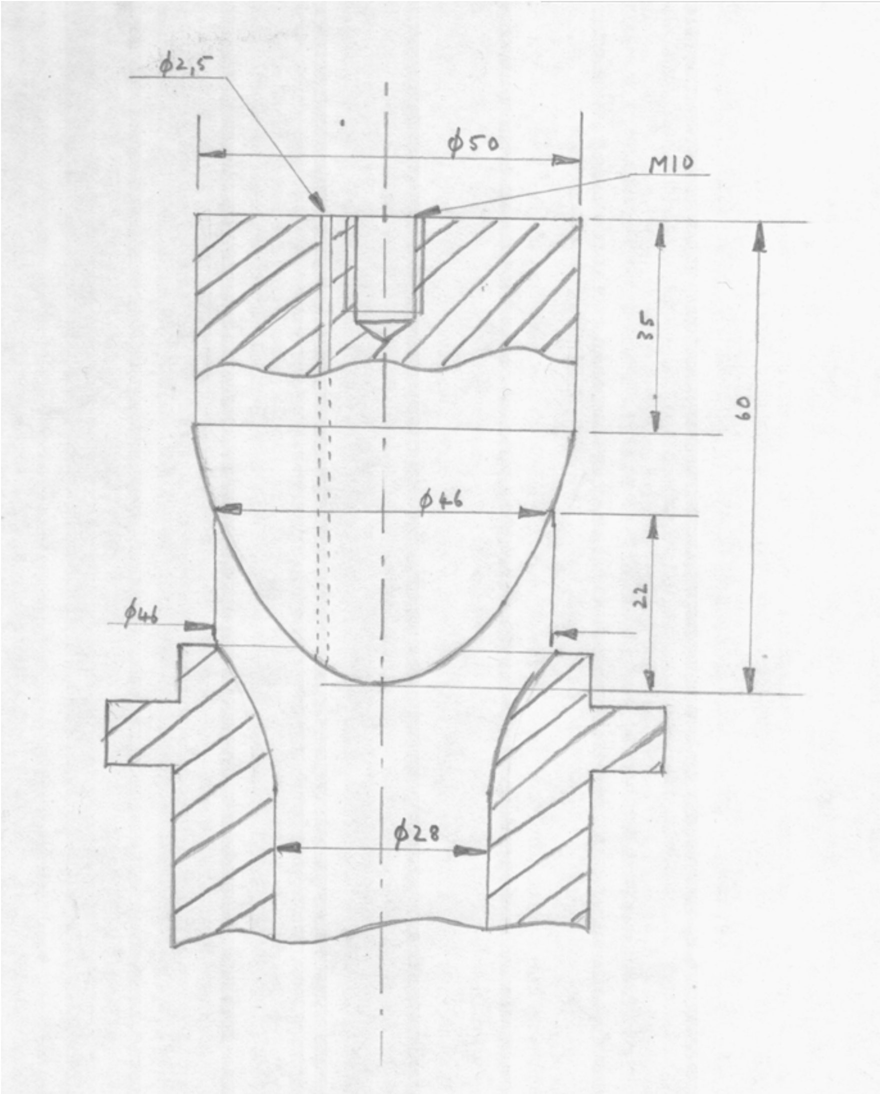


Figure D.5: Assembly drawing of 40%-scaled stopper and SEN upper part

# APPENDIX E

## E. Water model construction

### E.1 Construction process

The construction of the water model comprised of the following processes (in that particular order):

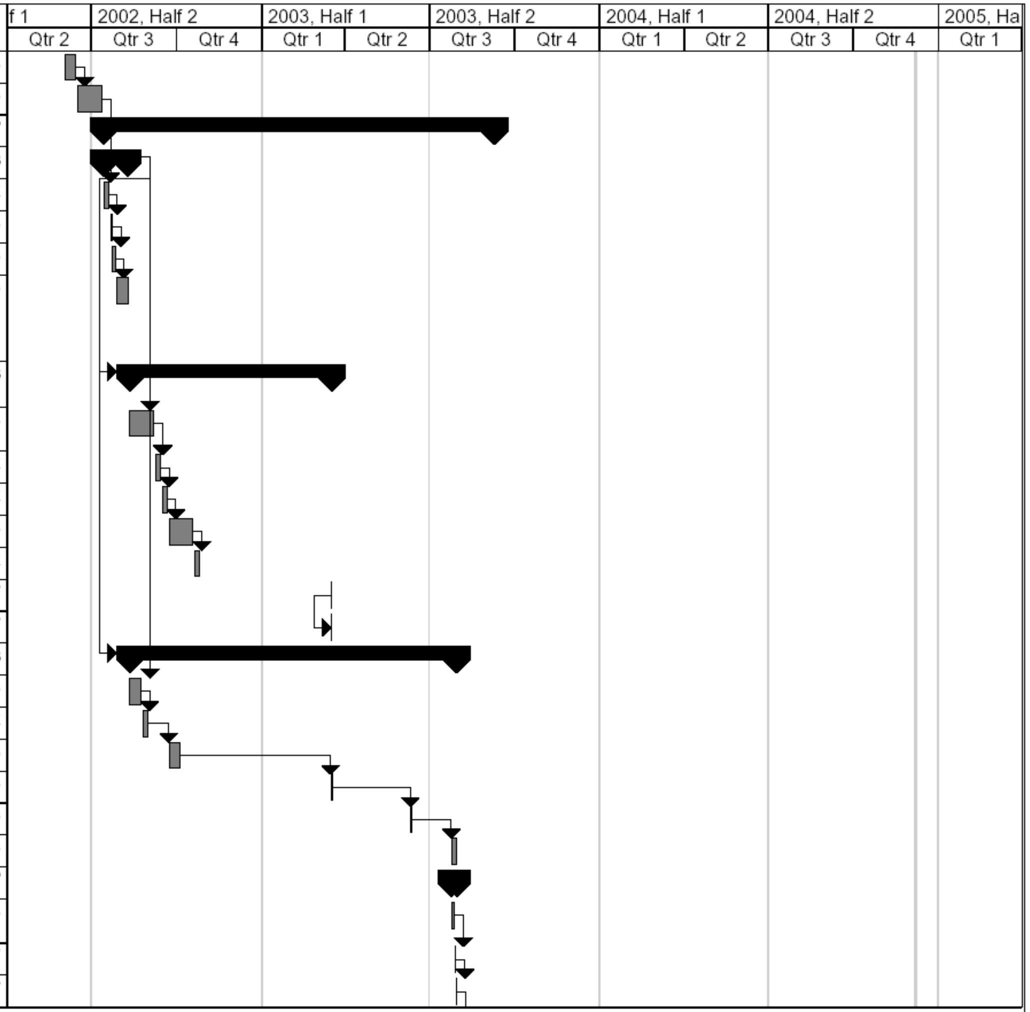
- Identify and order all loose parts and material
    - Steel for the frame
    - Bolts and nuts
    - Perspex
    - Pipes, elbows, T-sections, gate valves, reducers, pipe clips, plumber's tape, nipples (male to male BSP pipe sections), and all other small items to insignificant to mention
- Outsource of top tank, bottom tank and Aluminium SEN manufacturing
    - Prepare design drawings for manufacturing of top tank, bottom tank and SEN
    - Requesting quotations, placing the orders and co-ordinating payment of companies
    - Establish completion dates
    - Ensure that outsourced manufacturing quality is sufficient and ensure integration of outsourced components into final water model product
- Frame construction
    - Mark-off using specially designed die for accurate, repeatable marking on angled sections for holes
    - Drill of holes
    - Construction of frame
    - Preliminary fitment of perspex mould to establish position of holes in the hanging beams
    - Manufacturing of extra long bolts, using threaded rods and nuts
    - Paint for aesthetic purposes and to prevent rust

- Perspex mould construction
    - Prepare drawings for perspex sheet sizes and information for narrow wall cuts
    - Establish a seal mechanism between the narrow walls and wide walls, as well as between the perspex mould and the bottom tank
    - Manufacture narrow walls by bonding 3 perspex sheets (cut to size) together
- Pipes, T-pieces, valves, etc.
    - Take into account all distances of pipes and T-pieces to ensure location of water model remains in the desired position
    - Ensure all connections are leak-free
- Pump installation
    - The installation of the pump was postponed until high speed tests are desired

## E.2 <u>Construction Gantt-chart</u>

Refer to the following page(s) for the Gantt-chart of the construction process of the water model.

| ID | Task Name | Duration |
|---|---|---|
| 1 | Concept design | 2 wks |
| 2 | Detail design | 4 wks |
| 3 | **Construction** | **302 days?** |
| 4 | **Identify all material and loose parts** | **20 days** |
| 5 | Steel for frame | 1 wk |
| 6 | Bolts and nuts | 2 days |
| 7 | Perspex | 3 days |
| 8 | Pipes, elbows, T-sections, gate valves, reducers, pipe clips, plumber's tape, nipples (male to male BSP pipe sections), and all other small items to insignificant to mention | 2 wks |
| 9 | **Outsourcing of top tank, bottom tank and Aluminium SEN** | **156 days** |
| 10 | Prepare design drawings for manufacturing of top tank, bottom tank and SEN [Sept-Okt] | 4 wks |
| 11 | Request quotations | 1 wk |
| 12 | Place orders | 1 wk |
| 13 | Coordinating payments | 4 wks |
| 14 | Ensure quality of outsourced components | 1 wk |
| 15 | Receive Aluminium SEN | 1 day |
| 16 | Receive top and bottom tank | 1 day |
| 17 | **Frame design and construction** | **253 days** |
| 18 | Design and manufacture special mark-off die | 2 wks |
| 19 | Mark-off | 1 wk |
| 20 | Cut correct lengths and drill holes | 2 wks |
| 21 | Construction of frame | 2 days |
| 22 | Preliminary fitment of perspex sheets | 2 days |
| 23 | Paint for esthetic purposes and to prevent rust | 4 days |
| 24 | **Perspex mould construction** | **5 days?** |
| 25 | Prepare drawings for perspex sheet sizes and mould walls | 2 days |
| 26 | Fit bottom, top tanks | 1 day? |
| 27 | Establish seal mechanism | 1 day |

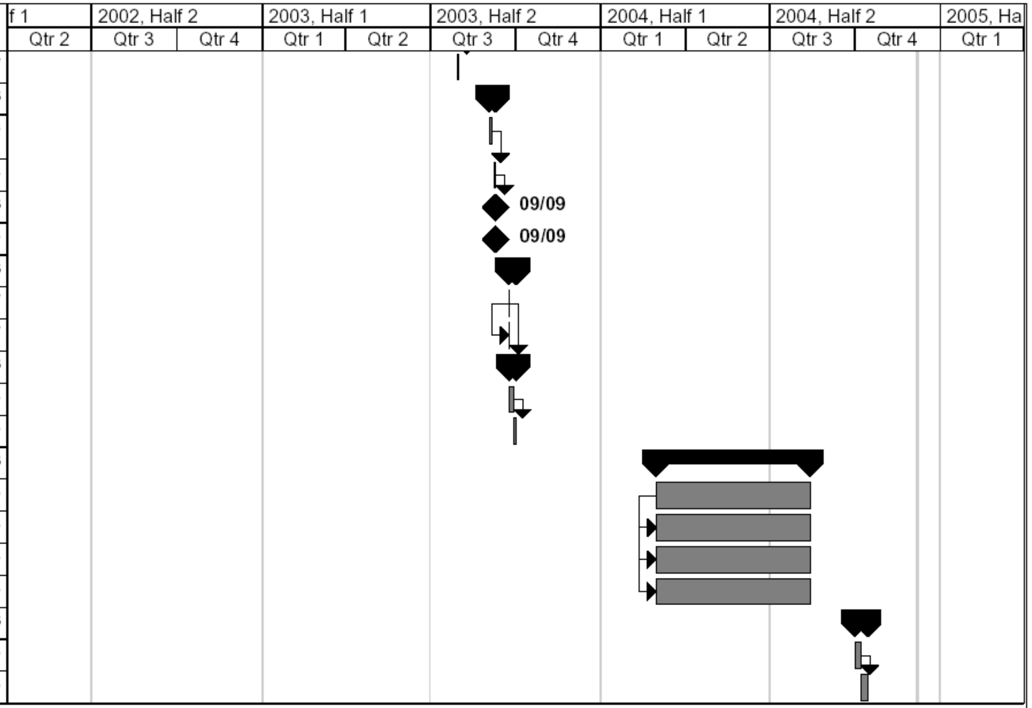



Project: Watermodel_Gantt
Date: 2004/12/07

| Task | Milestone | External Tasks |
|---|---|---|
| Split | Summary | External Milestone |
| Progress | Project Summary | Deadline |

Page 1

| ID | Task Name | Duration |
|---|---|---|
| 28 | Manufacture narrow walls: glue | 1 day |
| 29 | **Pipes, T-pieces, valves etc.** | **5 days** |
| 30 | Measure pipe lengths and valve lengths: location of water model 12 September ope dag... | 3 days |
| 31 | Ensure connections are leak-free | 2 days |
| 32 | **Pump installation** | **0 days** |
| 33 | Cancelled | 0 days |
| 34 | **Commissioning 24 Sept** | **6 days** |
| 35 | Leak-test | 1 day |
| 36 | Preliminary water model test | 1 day |
| 37 | **Water model tests: 2003 (10 - 14 Nov)** | **5 days** |
| 38 | Water model test: 1575mm (full-scale); Old SEN | 2.5 days |
| 39 | Water model test: 1575mm (full-scale); New SEN | 2.5 days |
| 40 | **Water model upgrade (Marius Botha)** | **120 days** |
| 41 | New carbon perspex sheet | 120 days |
| 42 | Install flow meter | 120 days |
| 43 | Strengthen critical columns | 120 days |
| 44 | Aluminium SEN insert: new design | 120 days |
| 45 | **Water model tests: 2004** | **10 days** |
| 46 | Water model test: 1060mm (full-scale); Old/New | 5 days |
| 47 | Water model test: 1250mm (full-scale); Old/New | 5 days |




Project: Watermodel_Gantt
Date: 2004/12/07

Task | Split | Progress | Milestone | Summary | Project Summary | External Tasks | External Milestone | Deadline

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# APPENDIX F

## F. Water model Results

### F.1 General

Two widths will be tested for both SEN designs, each at two different flow speeds (equivalent to casting speeds) and two different submergence depths:

- Widths: 1060mm and 1250mm
- Submergence depths: 80mm and 150mm
- Water model flow rates satisfying Fr-similarity for a casting speed of 1.0 m/min
    - 1060mm width: 1.28 $m^3/h$
    - 1250mm width: 1.52 $m^3/h$

### F.2 Visualisation methods

Although the flow field is assumed to be steady (does not change with passing time), a dye injected into the top of the SEN will highlight the steady flow patterns. However, as the jet mixes with the water in the mould cavity, the jet becomes less visible until the entire mould cavity is the same colour. The double barrel and upward swirling of the jets can also be visualised.

In order to illustrate the three-dimensional flow field, the results will be shown as a series of 4 “snapshots”, exactly as the water model test would unfold before an observer.

## F.3 Results

The water model results of the experiments (listed in Table F.1) will be presented in Figures F.1 to F15. All tests were performed for casting speeds of 1.0m/min and 1.1 m/min (satisfying Fr-similarity). However, the results for the two different flow rates were almost identical (as shown in Figures F.1 and F.2). Consequently, only the results of the 1.0 m/min casting speed tests are displayed in this Appendix.

Table F.1: List of water model experiments and reference Figure number

| **Figure F.** | **SEN design** | **Mould Width (full-scale) [mm]** | **Submergence depth (full-scale) [mm]** | **$Q_{model}$[1] (Fr-similarity) [$m^3/h$]** | **$v_{cast}$ (full-scale) [m/min]** |
|---|---|---|---|---|---|
| 1 | Old | 1060 | 150 | 1.42 | 1.1 |
| 2 | Old | 1060 | 150 | 1.28 | 1.0 |
| 3 | New | 1060 | 150 | 1.28 | 1.0 |
| 4 | Old | 1060 | 80 | 1.28 | 1.0 |
| 5 | New | 1060 | 80 | 1.28 | 1.0 |
| 6 | Old | 1250 | 150 | 1.52 | 1.0 |
| 7 | New | 1250 | 150 | 1.52 | 1.0 |
| 8 | Old | 1250 | 80 | 1.52 | 1.0 |
| 9 | New | 1250 | 80 | 1.52 | 1.0 |

[1] Refer to Chapter 3 for derivation of **eq 3-7** used to calculate the flow rate of the model, satisfying Fr-similarity.

Old SEN, 1060 mm width, 150mm submergence depth, 1.1 m/min full-scale cast speed

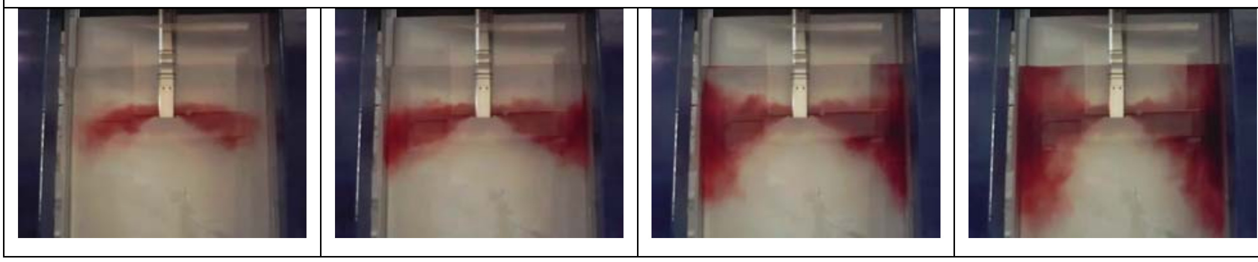


Figure F.1: Old SEN (1060mm width, 150mm submergence depth, 1.1 m/min full-scale cast speed) snapshots

Old SEN, 1060 mm width, 150mm submergence depth, 1.0 m/min full-scale cast speed

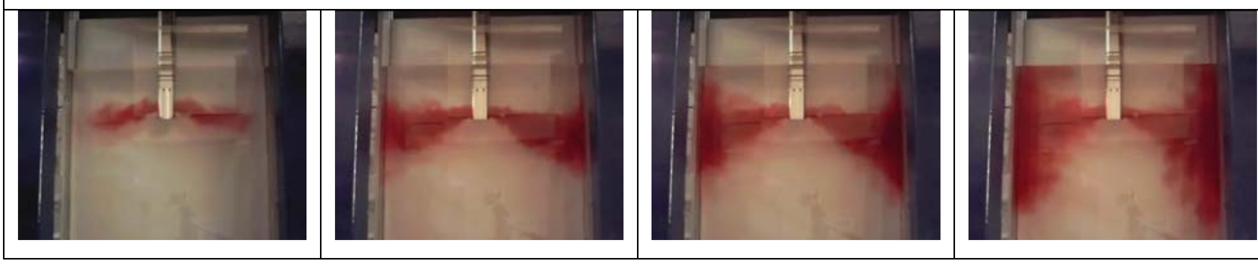


Figure F.2: Old SEN (1060mm width, 150mm submergence depth, 1.0 m/min full-scale cast speed) snapshots

New SEN, 1060 mm width, 150mm submergence depth, 1.0 m/min full-scale cast speed

Figure F.3: New SEN (1060mm width, 150mm submergence depth, 1.0 m/min full-scale cast speed) snapshots

Old SEN, 1060 mm width, 80mm submergence depth, 1.0 m/min full-scale cast speed

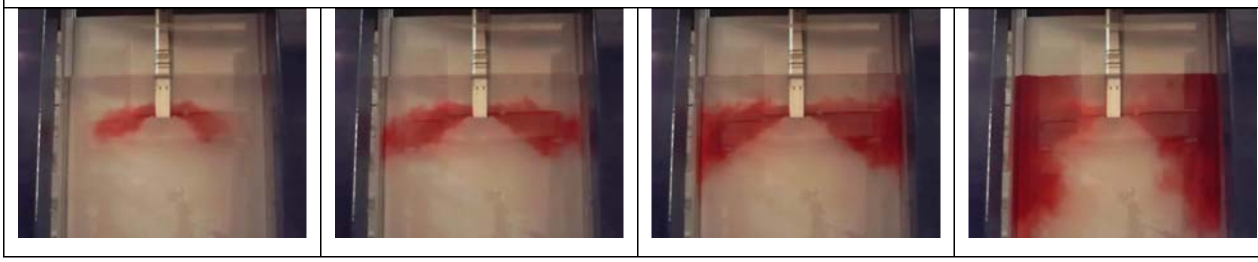


Figure F.4: Old SEN (1060mm width, 80mm submergence depth, 1.0 m/min full-scale cast speed) snapshots

New SEN, 1060 mm width, 80mm submergence depth, 1.0 m/min full-scale cast speed

Figure F.5: New SEN (1060mm width, 80mm submergence depth, 1.0 m/min full-scale cast speed) snapshots

Old SEN, 1250 mm width, 150mm submergence depth, 1.0 m/min full-scale cast speed

Figure F.6: Old SEN (1250mm width, 150mm submergence depth, 1.0 m/min full-scale cast speed) snapshots

New SEN, 1250 mm width, 150mm submergence depth, 1.0 m/min full-scale cast speed

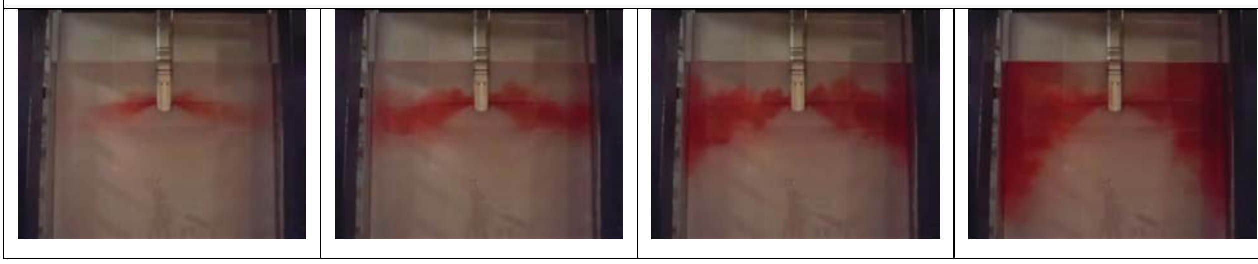


Figure F.7: New SEN (1250mm width, 150mm submergence depth, 1.0 m/min full-scale cast speed) snapshots

Old SEN, 1250 mm width, 80mm submergence depth, 1.0 m/min full-scale cast speed

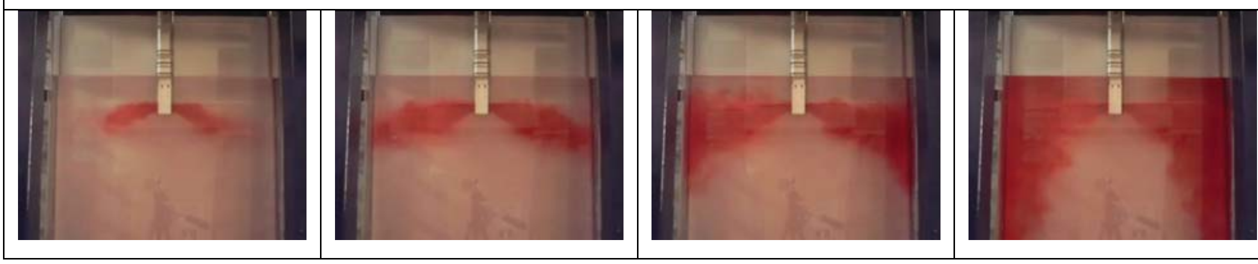


Figure F.8: Old SEN (1250mm width, 80mm submergence depth, 1.0 m/min full-scale cast speed) snapshots

New SEN, 1250 mm width, 80mm submergence depth, 1.0 m/min full-scale cast speed

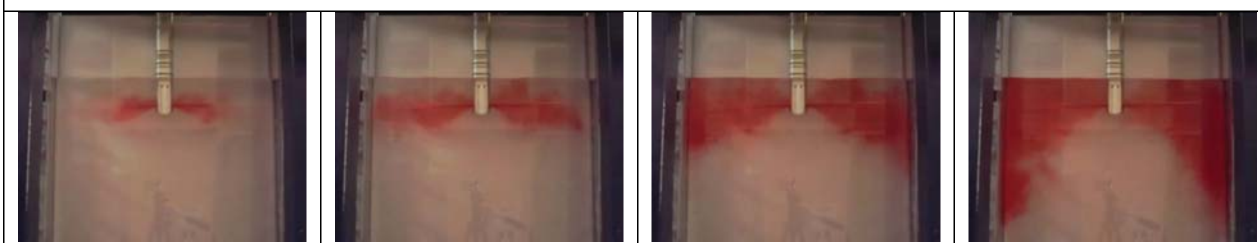


Figure F.9: New SEN (1250mm width, 80mm submergence depth, 1.0 m/min full-scale cast speed) snapshots

# APPENDIX G

## G. Columbus Stainless base case SEN design: drawings

### G.1 Base case SEN design: general

Although the base case SEN design (also referred to as the Old SEN) is described in the main text, the basic parameters and description will be repeated for the sake of completeness.

Typical old SEN parameters:

- SEN total length: 1100 mm
- Shape: morphs from circular cross section (top) to a rectangular cross section (bottom)
- Design type: Bifurcated ports without a well
- Port height: 70 mm
- Port width: 45 mm
- Port radii: 35mm (all radii on ports)
- Port angle: 15 º upwards
- Typical submergence depths: 80 mm – 200mm (defined from the top of the port to the meniscus surface)

### G.2 Base case SEN: drawings (copyright)

Refer to Figure G.1 below for the drawings of the old SEN of Columbus Stainless, Middelburg, South Africa.

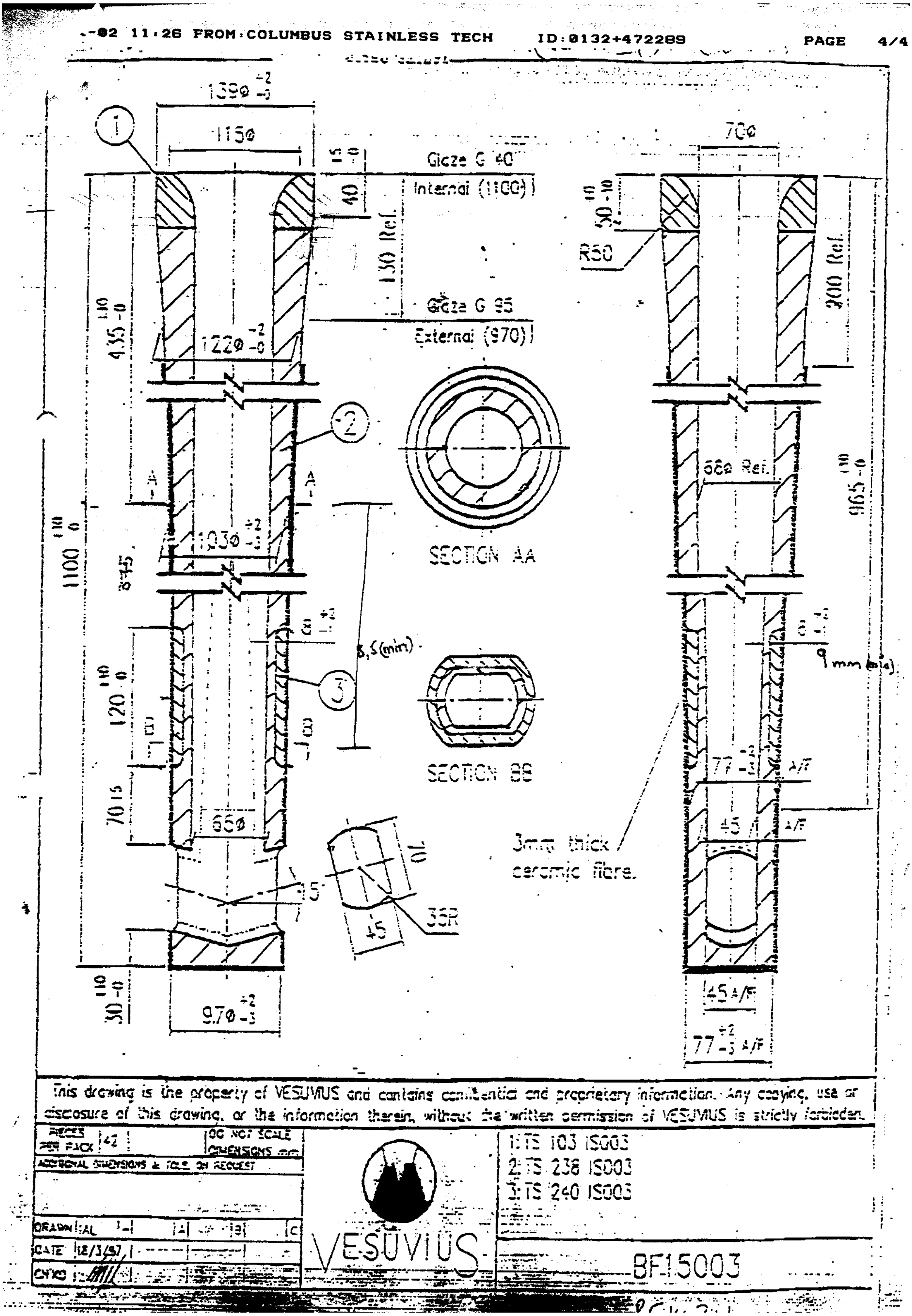



Figure G.1: Old SEN Columbus Stainless: Official Drawings (copyright Vesuvius)

# APPENDIX H

## H. Columbus Stainless new SEN design: drawings

### H.1 New SEN design: general

As the new SEN design is mostly used for comparisons in an effort to optimise the CFD model for later optimisation, the details of this design will only be presented in this Appendix.

Columbus Stainless made use on this design type a few months after this study commenced with their old SEN design as the original base case. The main difference between the new SEN and the previous SEN (base case for Chapter 4) is that a well (40mm depth) is made provision for, at the cost of smaller port heights (only 60mm instead of 70mm). The angle of both bifurcated nozzle ports remain at an angle of 15º upwards.

The rest of the SEN design is identical to the old SEN, as can be verified by comparing the drawings of the new design (Figure H.1 below) with that of the old base case SEN (Figure G.1 in Appendix G).

The effect of the perceived small changes (well added and port height reduced) made to the old SEN is quite extensive, as pointed out in the main text and as depicted in Appendix F (water model experiments). This fact collaborates with a main assumption that justifies this study: small, inexpensive changes on the SEN can influence the flow pattern in the mould and resultant desired steel quality. The challenge is to quantify these changes (to design variables) in an effort to find an optimum (or optima) design(s).

## H.2 Base case SEN: drawings (copyright)

Refer to Figure H.1 below for the drawings of the new[1] SEN of Columbus Stainless, Middelburg, South Africa.

[1] This is the SEN currently (2003) in use at Columbus Stainless, Middelburg, South Africa.

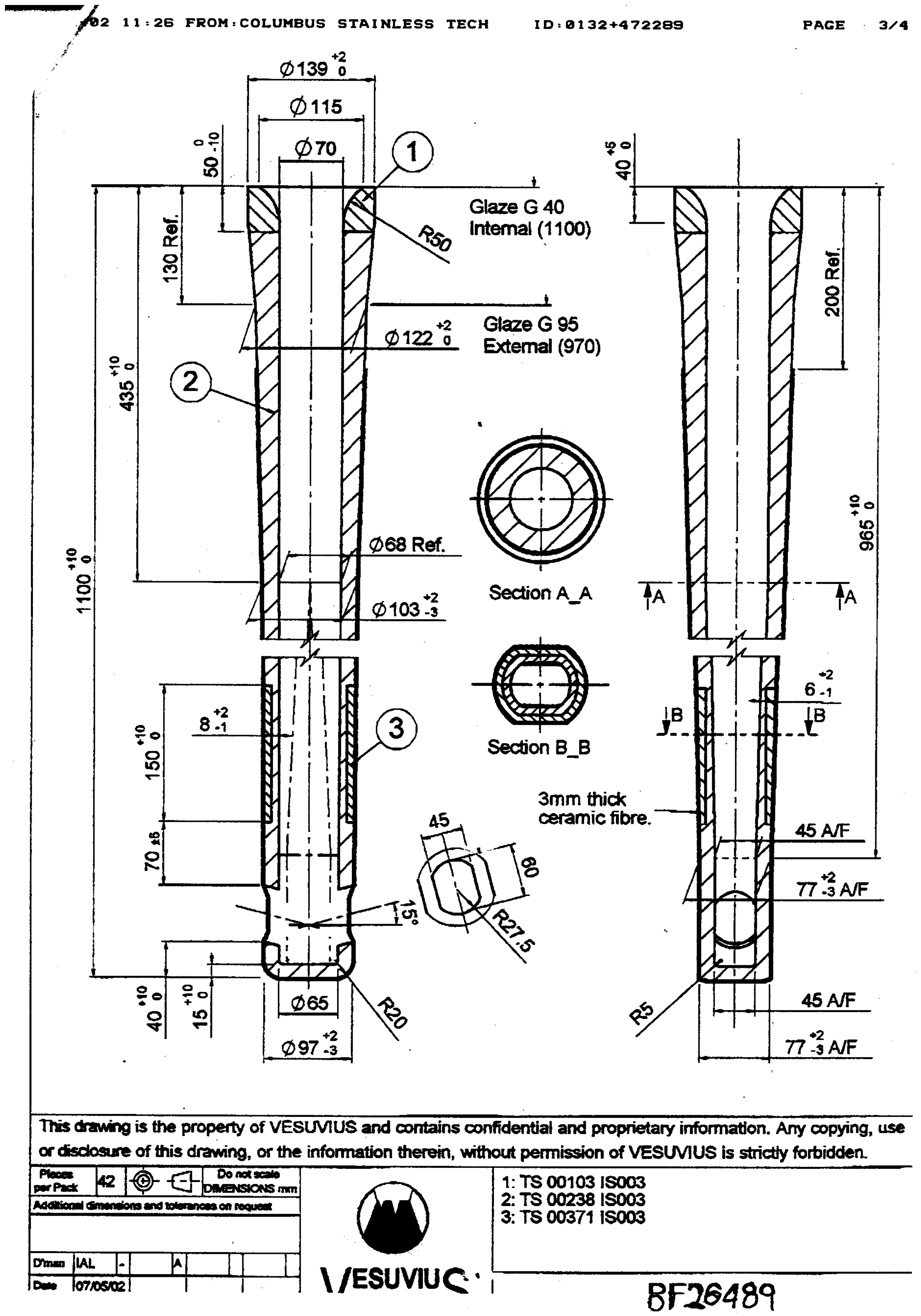



Figure H.1: New SEN Columbus Stainless: Official Drawings (copyright Vesuvius)

# APPENDIX I

## I. Comparison: meniscus boundary condition: Free surface vs. slip wall (zero-shear stress wall)

The comparison between the slip wall and free surface were conducted to ensure that the flow (of the steel or water) inside the mould is similar, irrespective of the type of boundary condition selected. The comparison in this Appendix is based on the base case (old SEN) and the new SEN.

The Volume of Fluid (VOF) method in FLUENT is used to evaluate a typical two-phase flow. The physical volume above the meniscus (or the free surface between the two phases) must be sufficiently large to ensure that a free atmosphere is simulated (refer to Figures I.1 and I.2)

The details of the comparisons are presented in Table I.1.

Table I.1: Details of comparison between the two boundary condition options (slip wall vs. free surface)

| **Figure I.** | **SEN design** | **Mould Width [mm]** | **Submergence depth (full-scale) [mm]** | **$Q_{model}$[1] (Fr-similarity) [$m^3/h$]** | **$v_{cast}$ (full-scale) [m/min]** |
|---|---|---|---|---|---|
| 1 | Old | 1575 | 200 | 1.72 | 1.0 |
| 2 | New | 1575 | 200 | 1.72 | 1.0 |

[1] Refer to Chapter 3 for derivation of **[eq 3-7]** used to calculate the flow rate of the model, satisfying Fr-similarity.

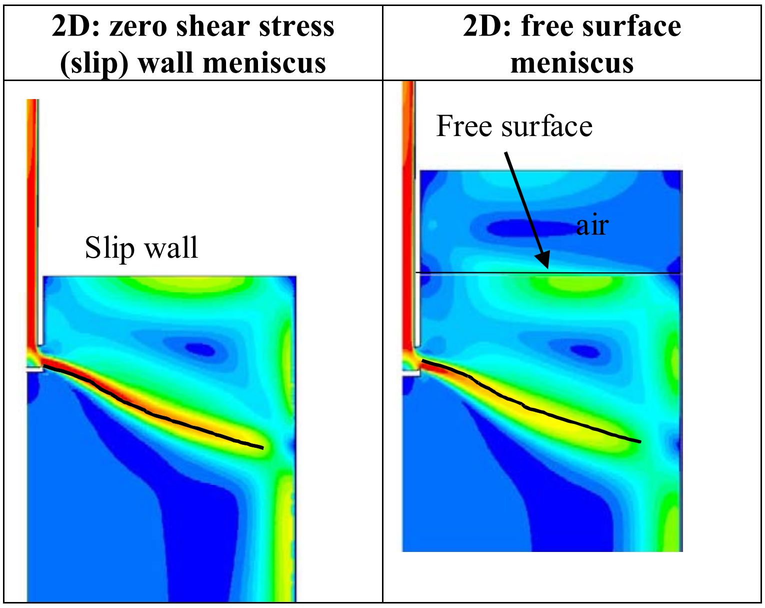



Figure I.1: 2D CFD-model meniscus boundary condition comparison: base case (**Old SEN**) (comparing velocity contours of magnitude)

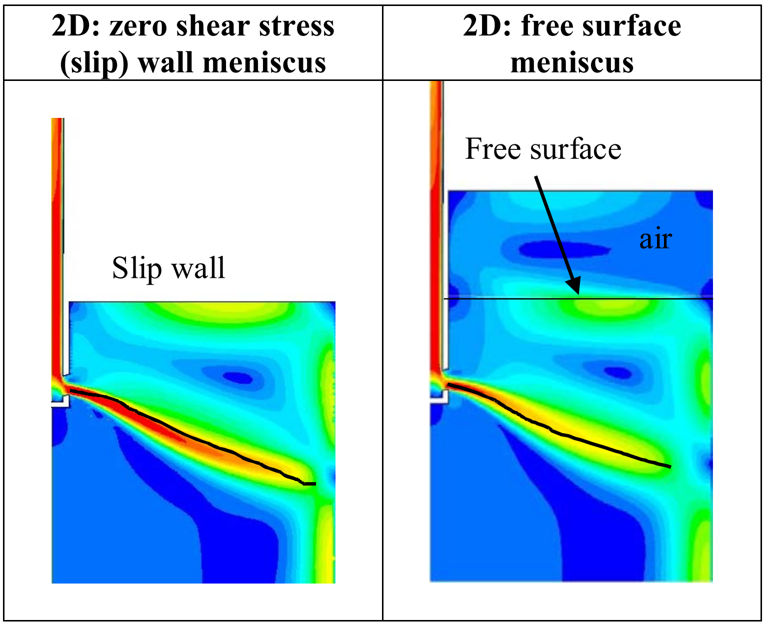



Figure I.2: CFD-model (2D) meniscus boundary condition comparison: base case (**New SEN**) (comparing velocity contours of magnitude)

*Discussion:*

As can be observed in the figures above, the difference between the flow patterns in the 2D CFD models using the different boundary conditions for the meniscus is remarkably negligible. The choice between a slip wall and free surface boundary condition is also assumed to have negligible influence on 3D CFD modelling.

The CFD models in both Figures I.1 and I.2 above are momentum-only models, and subsequently imitate the physical water model experiments (water as fluid, no temperature effects). When temperature effects have to be included in the CFD models (as have been later in Chapter 4 and throughout Chapter 5), a heat extraction flux has to be included in the boundary condition of the meniscus surface. Using a slip (or rather zero-shear stress) wall, a heat extraction heat flux can easily be added to this wall as a boundary condition. Currently, using the VOF-method, it is very difficult to obtain the same result, as a heat flux need to be specified on top of the air layer (refer to Figures I.1 and I.2). Subsequently, the exact heat flux over the free surface (interface between phase 1 and phase 2) cannot be determined exactly.

However, as mentioned in the main text, when meniscus behaviour becomes important for exact meniscus layer simulation, the free surface VOF-method necessarily needs to be employed.

Nevertheless, for the purposes of this study (including optimisation in Chapter 5), the meniscus boundary condition will be a zero-shear stress wall. The heat flux through the meniscus slip wall will be added when necessary (when plant conditions and circumstances are modelled using the energy equation in FLUENT).

# APPENDIX J

## J. GAMBIT script file (for automatic geometry and mesh rendering)

### J.1 General

In order for one to later edit the GAMBIT script file, it is customary to make notes in the script file, which must obviously be ignored by the GAMBIT interpreter. Thus, all text in a line following a forward slash or "/", are notes and will be ignored.

*Exceptions and parameterisation:*

The script file (below in section J.2) may seem excessively long for creating a mere 2D geometry and mesh.

The reason for this is that certain exceptions may occur whenever the port angle varies from positive to negative (for example):

- different equations might be necessary
- different reference points or vertices are necessary to compute next vertex positions

*Categories in typical GAMBIT script file*

The typical GAMBIT script file usually contains the following tasks in this specific order (exactly the same order in which a "manual" geometry and mesh would have been generated using GAMBIT's GUI):

1. List all parameters (and dependent[1] variables)
2. Build model

   2.1 Create outline of geometry based on given parameters

[1] Dependent variables are variables that need to be defined as their values are determined by the chosen parameters or design variables.

2.2 Divide geometry into mesh-able areas and name areas (or volumes with a 3D model)

3. Mesh the geometry
4. Define and name all boundary surfaces

Refer to section J.2 on the following page for the GAMBIT script file used to generate 2D SEN and mould models (half models due to symmetry assumption).

## J.2 GAMBIT script file

The script file was used to create the geometry and mesh for 2D half models, similar to Figure 5.1 (Chapter 5).

```
/ Journal File for GAMBIT 2.0.4 :paramsen2d2.jou - vanaf paramsen2d1.jou


/ Nuwe leer vir 2d parametrisering



/1 Spesifisering en Beskrywing van veranderlikes


/ 11 Parameters (wat verander kan word)

/ $x1 = hoek van SENpoort met horisontaal in grade
/ $x3 = wydte van gietstuk in mm
/ $x4 = hoogte van poort in die middelsnit van poort (LW vir eers reeds h2d)(loodreg
op poort)
/ $x6 = lengte van gietstuk in mm
/ $x7 = meniskusposisie tov bo-punt van die poort (dus ondergedompelde diepte) in mm
/        [$x7 = 120 mm vir base case]
/ $x8 = diepte van versinking (LW: indien x8 = 0, dan verskil program later...)
/ $x9 = radius van poort - LW word eers later in aanmerking geneem
/ $x20 = h3d (loodreg) in mm ($x4 of h2d word later... dan hiervanaf bereken)
/ $x21 = wydte van poort in mm ($x4 of h2d word later... dan hiervanaf bereken)

$x1 = 15
$x3 = 1575
/ $x4
$x6 = 3000
$x7 = 120
$x8 = 0

$x9 = 35
$x20 = 70
$x21 = 45


/ 12 Berekening van h2d of $x4
 / Laat $x40 die area wees onder sirel vanaf 0 tot halfwydte van die poort
 / $x41 = halfwydte
 / Laat $x42 die gem_hoogte wees
 / dan is hlaer = radius - hgem
 / en dus h2d = h3d - 2*hlaer
 / inisialiseer eers
 $x40 = 0
 $x41 = 0
 $x42 = 0

 $x41 = $x21/2
 $x40 = (($x9*$x9)/2)*((DEG2RAD*(asin($x41/$x9))+($x41/($x9*$x9))*(sqrt(($x9*$x9)-
($x41*$x41)))) - 0)
 $x42 = $x40/($x41-0)
 $x4 = $x20 - 2*($x9 - $x42)


/ 13 Veranderlikes om bewerkings te verrig (word in GAMBIT bereken)

/ $x2 = meniskusafstand (y) vanaf globale oorsprong (funksie van x1 en x4 en x8) -
word self bereken
/ $x5 = poortas afstand van onderkant van SEN af in mm (funksie van x1, x4 en x8) -
word self bereken
/   LW: indien $x8>0, is die poortas nie meer relevant nie: bereken direk dy(A1-A2) =
x5
/ $x10 = veranderlike gebruik om pt A1 te skep
/ $x11 = veranderlike gebruik om pt A2 te skep
/ $x12 = veranderlike gebruik om pt A3 te skep
```

```
/ $x13 = veranderlike gebruik om pt A4 te skep
/ $x14 = veranderlike gebruik om pt A5 te skep (as x8 > 0 )
/ $x15, 16 = veranderlike gebruik om E1 en E2 te bereken
/ $x30 = veranderlike gebruik om koordinate aan te dui en klein berekeninkies te
voltooi
/ $x50, 51, 52 = veranderlikes gebruik om F1, F3 en F4 te bereken


/ 13 Inisialiseer alle berekeningsveranderlikes [is dit nodig?]
$x10 = 0
$x11 = 0
$x12 = 0
$x13 = 0
$x14 = 0
$x15 = 0
$x16 = 0
$x30 = 0




/2 Begin van modelbou

/ 21 Vaste punte (irrelevant van veranderlikes)
vertex create "C1" coordinates 0 0 0
vertex create "C2" coordinates 0 395 0
vertex create "C3" coordinates 0 435 0
vertex create "C4" coordinates 55 435 0
vertex create "C5" coordinates 35 395 0
vertex create "C6" coordinates 34 0 0
vertex create "C7" coordinates 0 -530 0
vertex create "C8" coordinates 32.5 -530 0
vertex cmove "C5" multiple 1 offset 50 0 0
vertex modify "vertex.9" label "T1"
edge create "C45" center2points "T1" "C5" "C4" minarc arc
vertex delete "T1"
vertex create "C9" coordinates 0 -665 0
vertex create "C10" coordinates 48.5 -665 0
edge create "C34" straight "C3" "C4"
edge create "C23" straight "C3" "C2"
edge create "C12" straight "C1" "C2"
edge create "C56" straight "C5" "C6"
edge create "C68" straight "C6" "C8"
edge create "C78" straight "C8" "C7"
edge create "C17" straight "C1" "C7"
edge create "C16" straight "C1" "C6"
edge create "C25" straight "C2" "C5"



/ Van hier af sal die joernaalleer verskil
///////////////////////////////////////////////////////////////////////////////
/ AFDELING 1
/ Geen insinking: dus $x8 = 0 - onthou else aan die einde en endif aan heel einde
IF COND ($x8 .EQ. 0)


/ 22 Skep van poortpunte A1 tot A4 en verbinding van pte

/ $x5 = poortas van onder af in mm - word vervolgens bereken
/ As hoek 0 is, maak effense positiewe hoek anders faal jou-leer
IF COND ($x1 .EQ. 0)
$x1 = 0.1
ENDIF

/ As hoek positief is,
IF COND ($x1 .GT. 0)
$x5 = 17.00446417 + (0.5*$x4)/(cos($x1))

/ As hoek negatief is
ELSE
$x5 = 17.00446417 + (0.5*$x4)/(cos($x1)) + 48.5*tan(-$x1)
ENDIF

$x10 = $x5 - (0.5*$x4)/(cos($x1))
vertex cmove "C9" multiple 1 offset 0 $x10 0
```

```
vertex modify "vertex.11" label "A1"
$x11 = 48.5*tan($x1)
vertex cmove "A1" multiple 1 offset 48.5 $x11 0
vertex modify "vertex.12" label "A2"

$x12 = $x4/(cos($x1))
vertex cmove "A2" multiple 1 offset 0 $x12 0
vertex modify "vertex.13" label "A3"

$x13 = 16*tan($x1)
vertex cmove "A3" multiple 1 offset -16 -$x13 0
vertex modify "vertex.14" label "A4"
/ LW: as x1 positief is, sal x13 positief wees: moet dus afgetrek word en vice versa

/verbind nou die punte
edge create "A1C7" straight "A1" "C7"
edge create "C8A4" straight "C8" "A4"
edge create "A43" straight "A4" "A3"
edge create "A32" straight "A3" "A2"
/ edge create "A21" straight "A2" "A1"
edge create "A2C10" straight "A2" "C10"
edge create "C109" straight "C10" "C9"



/ 23 Skep van punte B1 tot B4

/ Berekening van meniskushoogte tov oorsprong afhangend of die hoek x1 positief of
negatief is
IF COND ($x1 .GT. 0)
$x2 = 17.00446417 + $x4/cos($x1) + 48.5*tan($x1) + $x7 -665
ELSE
$x2 = 17.00446417 + $x4/cos($x1) + $x7 -665
ENDIF

vertex create "B1" coordinates 48.745265 $x2 0
$x30 = 0.5*$x3
vertex create "B2" coordinates $x30 $x2 0
vertex create "B3" coordinates $x30 -900 0
vertex create "B4" coordinates 0 -900 0

/ 24 Skep van punt D3
vertex create "D3" coordinates 0 -765 0

/ 25 Skep van punte E1 tot E4
/$x15 is die globale y-waarde van pt E1
$x15 = $x2 - 700
vertex create "E1" coordinates 0 $x15 0
vertex create "E2" coordinates $x30 $x15 0
$x16 = $x15 - ($x6 - 700)
vertex create "E3" coordinates $x30 $x16 0
vertex create "E4" coordinates 0 $x16 0

/ 26 Skep van punte F1 tot F4

vertex create "F1" coordinates $x30 -765 0
vertex create "F2" coordinates $x30 -665 0
/$x50 is x-afstand van pt A2,A3 na pt F3,F4
$x50 = $x30 - 48.5
vertex cmove "A2" multiple 1 offset $x50 0 0
vertex modify "vertex.28" label "F3"
vertex cmove "A3" multiple 1 offset $x50 0 0
vertex modify "vertex.29" label "F4"

/ 27 Skep pt G1 vir ekstra blok in SENpoortvlak
$x13 = 16*tan($x1)
vertex cmove "A2" multiple 1 offset -16 -$x13 0
vertex modify "vertex.30" label "G1"



/ 27 Verbind pte A, B D en E
edge create "A3B1" straight "A3" "B1"
edge create "B12" straight "B1" "B2"
edge create "B2F4" straight "B2" "F4"
edge create "A3F4" straight "A3" "F4"
```

```
edge create "F43" straight "F4" "F3"
edge create "A2F3" straight "A2" "F3"

edge create "F32" straight "F3" "F2"
edge create "C10F2" straight "C10" "F2"
edge create "F21" straight "F2" "F1"
edge create "D3F1" straight "D3" "F1"
edge create "F1B3" straight "F1" "B3"

edge create "B34" straight "B3" "B4"
edge create "B4D3" straight "B4" "D3"
edge create "D3C9" straight "D3" "C9"

edge create "B3E2" straight "B3" "E2"
edge create "B4E1" straight "B4" "E1"
edge create "E12" straight "E1" "E2"
edge create "E23" straight "E2" "E3"
edge create "E34" straight "E3" "E4"
edge create "E14" straight "E1" "E4"

edge create "A4G1" straight "A4" "G1"
edge create "A1G1" straight "A1" "G1"
edge create "G1A2" straight "G1" "A2"


/3 Skep van vlakke
face create "tuit" wireframe "C34" "C45" "C25" "C23"
face create "rgtskag" wireframe "C25" "C56" "C16" "C12"
face create "morfdeel" wireframe "C16" "C68" "C78" "C17"
face create "SENpoortLK" wireframe "C78" "C8A4" "A4G1" "A1G1" "A1C7"
face create "SENpoortRK" wireframe "A43" "A32" "G1A2" "A4G1"
face create "jetvol1" wireframe "A3B1" "B12" "B2F4" "A3F4"
face create "jetvol2" wireframe "A3F4" "F43" "A2F3" "A32"
face create "jetvol3" wireframe "F32" "C10F2" "A2C10" "A2F3"
face create "gietstuk1" wireframe "C10F2" "F21" "D3F1" "D3C9" "C109"
face create "gietstuk2" wireframe "D3F1" "F1B3" "B34" "B4D3"
face create "gietstuk3" wireframe "B34" "B3E2" "E12" "B4E1"
face create "ondergietstuk" wireframe "E12" "E23" "E34" "E14"



/4 Meshing
solver select "FLUENT 5/6"

/ 41 Pas vorm-funksie toe op meshvol
sfunction create sourceedges "A32" startsize 4 growthrate 1.1 distance 150 \
  sizelimit 10 attachfaces "meshvol" fixed

/ 42 Mesh alles behalwe ondergietstuk in onderstaande spesifieke volgorde

face mesh "SENpoortRK" map size 5
/maak "A3F4" in size 15 inkremente
/maak "A3B1" "C10A2" en "D3C9" in size 5 inkremente
face mesh "jetvolume2" submap size 15
face mesh "jetvolume1" submap size 15
face mesh "jetvolume3" submap size 15
/maak "D3F1" in size 15 inkremente
face mesh "gietstuk2" submap size 15
face mesh "gietstuk1" submap size 15
face mesh "gietstuk3" submap size 15

face mesh "rgtskag" map size 5
face mesh "morfdeel" map size 5
face mesh "tuit" map size 5
face mesh "SENpoortLK" map size 5


/ 43 Mesh nou ondergietstuk met uitrekfunksie
edge picklink "E23"
edge mesh "E23" firstlength ratio1 15 size 25
edge picklink "E14"
edge mesh "E14" firstlength ratio1 15 size 25
face mesh "ondergietstuk" map size 15
```

```
/5 RVW vir FLUENT

physics create "SENinlaat" btype "VELOCITY_INLET" edge "C34"
physics create "gietstuk_uitlaat" btype "PRESSURE_OUTLET" edge "E34"
physics create "SENmuur_buite" btype "WALL" edge "C45" "C56" "C68"
physics create "SENmuur_binne" btype "WALL" edge "A3B1" "A2C10" "C109"
physics create "SENpoortmuur_binne" btype "WALL" edge "C8A4" "A43" "G1A2" "A1G1"
physics create "gietstukmuur_nou" btype "WALL" edge "B2F4" "F43" "F32" "F21" "F1B3"
"B3E2"
physics create "ondermould_nou" btype "WALL" edge "E23"
physics create "simmetrie_nou" btype "SYMMETRY" edge "C23" "C12" \
  "C17" "A1C7" "D3C9" "B4D3" "B4E1" "E14"
physics create "meniskusvlak" btype "WALL" edge "B12"
physics create "meshvolvlak1" btype "INTERIOR" edge "A3F4"
physics create "meshvolvlak2" btype "INTERIOR" edge "A2F3"
physics create "binnemould_vlak" btype "INTERIOR" edge "B34"
physics create "ondermould_vlak" btype "INTERIOR" edge "E12"
physics create "SENpoortuitlaat" btype "INTERIOR" edge "A32"
physics create "ondertuit_vlak" btype "INTERIOR" edge "C25"
physics create "onderrgtskag_vlak" btype "INTERIOR" edge "C16"
physics create "ondermorfdeel_vlak" btype "INTERIOR" edge "C78"


//////////////////////////////////////////////////////////////////////////////////////
/////
/AFDELING 2
/ Insinking vind wel plaas: Dus $x8 > 0

/ Optimering randvoorwaardes
/ LW: As x1 > 0 deg; moet x8 > 32.5*tan(x1)
/     As x1 < 0 deg; moet x8 > 16*tan(-x1)

ELSE

/ 22 Skep van poortpunte A1 tot A6 en verbinding van pte

/ $x5 = dy van A1 na A2 in mm - word vervolgens bereken
/ As hoek 0 is, maak effense positiewe hoek anders faal jou-leer
IF COND ($x1 .EQ. 0)
$x1 = 0.1
ENDIF

$x5 = 15 + $x8 + 16*tan($x1)
vertex cmove "C9" multiple 1 offset 0 15 0
vertex modify "vertex.11" label "A1"
vertex cmove "C10" multiple 1 offset 0 $x5 0
vertex modify "vertex.12" label "A2"

$x12 = $x4/(cos($x1))
vertex cmove "A2" multiple 1 offset 0 $x12 0
vertex modify "vertex.13" label "A3"

$x13 = 16*tan($x1)
vertex cmove "A3" multiple 1 offset -16 -$x13 0
vertex modify "vertex.14" label "A4"
/ LW: as x1 positief is, sal x13 positief wees: moet dus afgetrek word en vice versa

vertex cmove "A1" multiple 1 offset 32.5 0 0
vertex modify "vertex.15" label "A5"
vertex cmove "A5" multiple 1 offset 0 $x8 0
vertex modify "vertex.16" label "A6"


/verbind nou die punte
edge create "A1C7" straight "A1" "C7"
edge create "C8A4" straight "C8" "A4"
edge create "A43" straight "A4" "A3"
edge create "A32" straight "A3" "A2"
edge create "A26" straight "A2" "A6"
edge create "A65" straight "A6" "A5"
edge create "A51" straight "A5" "A1"
edge create "A46" straight "A4" "A6"

edge create "A2C10" straight "A2" "C10"
edge create "C109" straight "C10" "C9"
```

```
/ 23 Skep van punte B1 tot B4

/ Berekening van meniskushoogte tov oorsprong ongeag of die hoek x1 positief of
negatief is
$x2 = 15 + $x8 + 16*tan($x1) + $x4/cos($x1) + $x7 -665

vertex create "B1" coordinates 48.745265 $x2 0
$x30 = 0.5*$x3
vertex create "B2" coordinates $x30 $x2 0
vertex create "B3" coordinates $x30 -900 0
vertex create "B4" coordinates 0 -900 0


/ 24 Skep van punte D3
vertex create "D3" coordinates 0 -765 0

/ 25 Skep van punte E1 tot E4
/ $x15 is die globale y-waarde van pt E1
$x15 = $x2 - 700
vertex create "E1" coordinates 0 $x15 0
vertex create "E2" coordinates $x30 $x15 0
$x16 = $x15 - ($x6 - 700)
vertex create "E3" coordinates $x30 $x16 0
vertex create "E4" coordinates 0 $x16 0


/ 26 Skep van punte F1 tot F4

vertex create "F1" coordinates $x30 -765 0
vertex create "F2" coordinates $x30 -665 0
/$x50 is x-afstand van pt A2,A3 na pt F3,F4
$x50 = $x30 - 48.5
vertex cmove "A2" multiple 1 offset $x50 0 0
vertex modify "vertex.30" label "F3"
vertex cmove "A3" multiple 1 offset $x50 0 0
vertex modify "vertex.31" label "F4"


/  27 Verbind pte A, B D en E

edge create "A3B1" straight "A3" "B1"
edge create "B12" straight "B1" "B2"
edge create "B2F4" straight "B2" "F4"
edge create "A3F4" straight "A3" "F4"
edge create "F43" straight "F4" "F3"
edge create "A2F3" straight "A2" "F3"

edge create "F32" straight "F3" "F2"
edge create "C10F2" straight "C10" "F2"
edge create "F21" straight "F2" "F1"
edge create "D3F1" straight "D3" "F1"
edge create "F1B3" straight "F1" "B3"

edge create "B34" straight "B3" "B4"
edge create "B4D3" straight "B4" "D3"
edge create "D3C9" straight "D3" "C9"

edge create "B3E2" straight "B3" "E2"
edge create "B4E1" straight "B4" "E1"
edge create "E12" straight "E1" "E2"
edge create "E23" straight "E2" "E3"
edge create "E34" straight "E3" "E4"
edge create "E14" straight "E1" "E4"


/3 Skep van vlakke

face create "tuit" wireframe "C34" "C45" "C25" "C23"
face create "rgtskag" wireframe "C25" "C56" "C16" "C12"
face create "morfdeel" wireframe "C16" "C68" "C78" "C17"
face create "SENpoortLK" wireframe "C78" "C8A4" "A46" "A65" "A51" "A1C7"
face create "SENpoortRK" wireframe "A43" "A32" "A26" "A46"
face create "jetvol1" wireframe "A3B1" "B12" "B2F4" "A3F4"
```

```
face create "jetvol2" wireframe "A3F4" "F43" "A2F3" "A32"
face create "jetvol3" wireframe "F32" "C10F2" "A2C10" "A2F3"
face create "gietstuk1" wireframe "C10F2" "F21" "D3F1" "D3C9" "C109"
face create "gietstuk2" wireframe "D3F1" "F1B3" "B34" "B4D3"
face create "gietstuk3" wireframe "B34" "B3E2" "E12" "B4E1"
face create "ondergietstuk" wireframe "E12" "E23" "E34" "E14"



/4 Meshing
solver select "FLUENT 5/6"


face mesh "SENpoortRK" map size 5
/maak "A3F4" in size 15 inkremente
/maak "A3B1" "C10A2" en "D3C9" in size 5 inkremente
face mesh "jetvolume2" submap size 15
face mesh "jetvolume1" submap size 15
face mesh "jetvolume3" submap size 15
/maak "D3F1" in size 15 inkremente
face mesh "gietstuk2" submap size 15
face mesh "gietstuk1" submap size 15
face mesh "gietstuk3" submap size 15

face mesh "rgtskag" map size 5
face mesh "morfdeel" map size 5
face mesh "tuit" map size 5
face mesh "SENpoortLK" map size 5


/ 43 Mesh nou ondergietstuk met uitrekfunksie
edge picklink "E23"
edge mesh "E23" firstlength ratio1 15 size 25
edge modify "E41" backward
edge picklink "E41"
edge mesh "E41" firstlength ratio1 15 size 25
face mesh "ondergietstuk" map size 15



/5 RVW vir FLUENT
physics create "SENinlaat" btype "VELOCITY_INLET" edge "C34"
physics create "gietstuk_uitlaat" btype "PRESSURE_OUTLET" edge "E34"
physics create "SENmuur_buite" btype "WALL" edge "C45" "C56" "C68"
physics create "SENmuur_binne" btype "WALL" edge "A3B1" "A2C10" "C109"
physics create "SENpoortmuur_binne" btype "WALL" edge "C8A4" "A43" "A26" "A65" "A51"
physics create "gietstukmuur_nou" btype "WALL" edge "B23" "B3E2"
physics create "ondermould_nou" btype "WALL" edge "E23"
physics create "simmetrie_nou" btype "SYMMETRY" edge "C23" "C12" \
  "C17" "A1C7" "D3C9" "B4D3" "B4E1" "E41"
physics create "meniskusvlak" btype "WALL" edge "B1D1" "D1B2"
physics create "meshvolvlak1" btype "INTERIOR" edge "D12"
physics create "meshvolvlak2" btype "INTERIOR" edge "D23"
physics create "binnemould_vlak" btype "INTERIOR" edge "B34"
physics create "ondermould_vlak" btype "INTERIOR" edge "E12"
physics create "SENpoortuitlaat" btype "INTERIOR" edge "A32"
physics create "ondertuit_vlak" btype "INTERIOR" edge "C25"
physics create "onderrgtskag_vlak" btype "INTERIOR" edge "C16"
physics create "ondermorfdeel_vlak" btype "INTERIOR" edge "C78"


ENDIF
/ einde van groot IF-stellling, nl die x8 > 0 of x8 = 0
```

# APPENDIX K

## K. FLUENT script file (for set-up and run)

### K.1 General

Unlike the GAMBIT script files, the FLUENT commands are more explanatory; consequently less notes need to be made by the user. However, notes can be made by inserting an exclamation mark or "!" in the beginning of the line – the line will be ignored.

As explained in Chapter 5, the Optimiser (LS-OPT) acts as coordinator for the optimisation process. Consequently, all values indicated between double greater than – smaller than signs ("<<value>>") are controlled by LS-OPT. The first example in the FLUENT script file in section K.2, is <<inlaatsnelheid>>, which is the inlet velocity specified by LS-OPT, as the inlet velocity is computed from the cast speed in the LS-OPT com-file (refer to Appendix L).

*Tasks to be performed by typical FLUENT script file:*

The FLUENT script file is used to perform the following tasks (in that specific order):

1. Set-up
   - Import mesh file from GAMBIT
   - Test mesh file for integrity
   - Define models
     - energy model on/off
     - turbulence model and accompanying settings
   - Define materials and material properties
   - Define operating conditions
   - Define all boundary conditions (and insert values)
     - Inlet: velocity inlet

    - Meniscus: zero shear stress wall
    - Outlet: pressure outlet
    - Mould walls
    - Symmetry faces
- Define and set-up monitors
    - E.g.: Maximum velocity magnitude on meniscus: record for each iteration. Specify files to write measurements to, etc.
- Initialise solution
- Ensure correct discretisation settings for momentum, pressure and energy

2. Run (solution procedure)
    - Set residual monitors and convergence criteria
    - Ensure discretisation schemes for pressure, momentum and turbulence model (k and ε in this case) is correct
    - Run procedure:
        - Set number of iterations
        - After each set of iterations, apply grid adaption to eradicate mass imbalances and ensure correct $y^+$ settings (refer to Chapter 4, section 4.4.3, for details)
        - Switch from first order discretisation to second order when sufficient initial convergence has been achieved
        - Adjust under- and over-relaxation factors according to predetermined solution procedure

Refer to section K.2 on the following page for the FLUENT script file, which performs the functions described above.

## K.2 FLUENT script file

```
!echo Gestadigde toestand: Opstelling - slegs momentum met moving walls: weergawe
2002-12-05
!echo LW Wees in regte directory: LW: vir pressure oulet, nie outflow:
!echo LW vir LSOPT met impakpt-grens asook turb_meniskus uitvoer en k_e_meniskus
uitvoer vir check
!echo Modifikasies Ken Craig
!echo Sit energievergelyking by met temperatuurrandwaardes en meniskus temp en
snelheid monitor
!echo Verhoog iterasies vir konvergensie van maks TKE
!echo Skryf meniskus temperatuur uit vir onttrekking van minimum waarde deur cat
!echo Skryf meniskus snelheid uit vir onttrekking van maksimum, negatief, waarde deur
cat
file/read-case
2dsen_mesh.msh
!echo 1 Grid
grid/check
grid/scale 0.001 0.001
define/models/energy yes no no no yes
define/units temperature c
!echo 2 Definieer modelle
define/models/viscous/ke-realizable yes
!echo 3 Definieer materiaal
define/materials/copy/fluid water-liquid
define/materials/change-create water-liquid steel yes constant 6975 yes constant 817.3
yes constant 30 yes constant 0.0064 yes 55.8 no no no no yes
define/boundary-conditions/fluid fluid yes steel no no yes 0 0 no no no
!echo 4 Definieer bedryfstoestande
define/operating-conditions/gravity yes 0 -9.81
!echo 5 Definieer RVW - onthou simmetrie bly dieselfde
!echo Fluent version 6.1 needs backflow direction specification method
define/boundary-conditions/velocity-inlet seninlaat no no yes yes no
<<inlaatsnelheid>> no <<inlaattemperatuur>> no no no yes 10 0.115
define/boundary-conditions/pressure-outlet gietstuk_uitlaat no 0 no
<<uitlaattemperatuur>> no yes no no no yes 10 <<Dhidroulies>>
define/boundary-conditions/wall meniskusvlak 0 no 0 no yes heat-flux no
<<hittevloedopmeniskus>> no yes shear-bc-spec-shear 0 0.5 no 0 no 0
define/boundary-conditions/wall ondermould_nou 0 no 0 no yes temperature no
<<wandtemperatuur>> yes motion-bc-moving no no <<SIgietspoed>> 0 -1 no 0 0.5
define/boundary-conditions/wall gietstukmuur_nou 0 no 0 no yes temperature no
<<wandtemperatuur>> yes motion-bc-moving no no <<SIgietspoed>> 0 -1 no 0 0.5
define/boundary-conditions/wall senpoortmuur_binne 0 no 0 no no no 0 no no 0 0.5
define/boundary-conditions/wall senmuur_buite 0 no 0 no no no 0 no no 0 0.5
define/boundary-conditions/wall senmuur_binne 0 no 0 no no no 0 no no 0 0.5
!echo 5b Verander temperatuur eenhede terug na K sodat temp monitor werk
define/units temperature k
!echo 6 Monitering
solve/monitors/residual plot yes print yes check-convergence yes yes yes yes yes yes q
q q
solve/monitors/surface/set-monitor ypluskant y-plus gietstukmuur_nou yes 1 yes yes
ypluskant.out "Vertex Average"
solve/monitors/surface/set-monitor max_ke_men turb-kinetic-energy meniskusvlak yes 2
yes yes turb_ke_men.out "Facet Maximum"
!echo 6a Sit minimum temperatuur monitor in
solve/monitors/surface/set-monitor min_temp_men temperature meniskusvlak yes 3 yes yes
tempmin_men.out "Facet Minimum"
!echo 6b Sit maksimum snelheids monitor in
solve/monitors/surface/set-monitor max_vel_men velocity-magnitude meniskusvlak

yes 4 yes yes velmax_men.out "Facet Maximum"
!echo 7 Inisialiseer
solve/initialize/compute-defaults/all-zones
solve/initialize/initialize-flow
!echo 8 Leer-hantering
file/auto-save/case-frequency 2000
file/auto-save/data-frequency 2000
file/auto-save/root-name 2dsentoets.gz
!echo 9 Kry druk d-s reg, nl PRESTO!
solve/set/ds/p 14
!echo 10 Konvergensie metode volg nou

!echo Gestadigde toestand: Slegs momentum - Konvergensiemetodiek: weergawe 2002-10-26
!echo 2D -geval
```

```
!echo 1st Order: LW: Probeer eers 1ste orde konvergeer
!echo 3 Stel kgensie kontinuiteit vir 5ordes 0.00001
solve/monitors/residual/convergence-crit 0.00001 0.001 0.001 0.000001 0.001 0.001
!echo 1 Itereer
solve/iter 500
!echo 5 2de Orde en p=PRESTO!
solve/set/ds/p 14
solve/set/ds/mom 1
solve/set/ds/k 1
solve/set/ds/e 1
solve/set/ds/temperature 1
!echo 6 Itereer
solve/iter 1500
!echo 7 Aanpas y+ en mi
adapt/aty+ 50 200 0 0 yes
adapt/miir no mass-imbalance -0.00001 0.00001
!echo adapt only in jet region y=-1m
adapt/mark-inout-rectangle yes no -100 100 -1 100
adapt/change-register

adapt/combine-register 0 1
adapt/atr

0 0 yes
!echo 8 Itereer
solve/iter 1000
!echo 9 Relax mom=0.4, k,e=0.7
solve/set/ur/mom 0.4
solve/set/ur/k 0.7
solve/set/ur/e 0.7
!echo 10 Itereer
solve/iter 2000
!echo 13 Save einde
file/write-c-d einde_run_2dsen_temp.gz
!echo 14 Skryf uit fluent_export_men_TKE.txt
file/export/ascii fluent_export_men_TKE.txt meniskusvlak

no yes turb-kinetic-energy q no

q
!echo 14a Skryf uit fluent_export_men_temp.txt
file/export/ascii fluent_export_men_temp.txt meniskusvlak

no yes temperature q yes

q
!echo 14b Skryf ui fluent_export_men_velmag.txt
file/export/ascii fluent_export_men_velmag.txt meniskusvlak

no yes velocity-magnitude q no q q
!echo 14c Skryf uit impakpt.txt
file/export/ascii impakpt.txt gietstukmuur_nou

no yes y-coordinate wall-shear q yes

q exit yes
```

# APPENDIX L

## L. LS-OPT com-file (for coordinating design optimisation process)

### L.1 General

The function of the LS-OPT com-file is explained in detail in Chapter 5, section 5.1.

Briefly, the com-file contains all information necessary for the entire optimisation process, including design variables, dependent variables, objective and constraint functions, as well as information to edit the GAMBIT and FLUENT script files (examples of these in Appendices J and K respectively) for automated optimisation.

*Tasks of the LS-OPT script file:*

The LS-OPT script file coordinates the optimisation process, and this function is best described using a diagram. The diagram from Chapter 5 section 5.1 is repeated here for the sake of completeness:

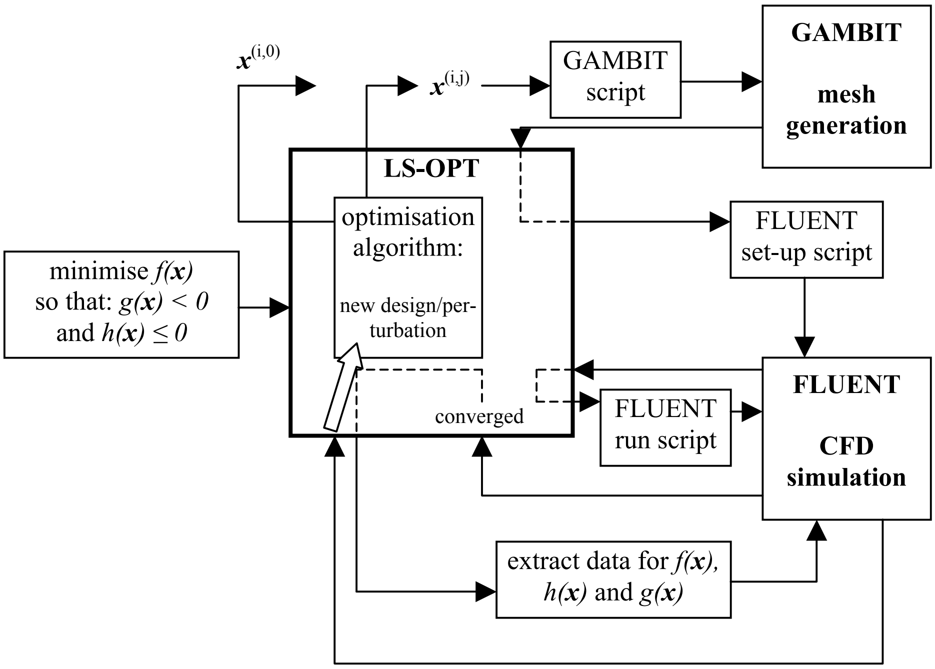



Figure L.1: Diagram depicting the tasks (including coordinating tasks) performed by LS-OPT during the design optimisation process

Refer to section L.2 for the LS-OPT com-file, which was used in the 2D design optimisation exercise presented in Chapter 5, section 5.5.

## L.2 LS-OPT com-file

```
"2D SEN optimering"
Author "Gideon Jacobus de Wet"
$ Created on Mon Nov 11 12:36:43 2002
solvers 1
responses 2
$
$ NO HISTORIES ARE DEFINED
$
$
$ DESIGN VARIABLES
$
variables 4
 Variable 'hoek' 15
  Lower bound variable 'hoek' -25
  Upper bound variable 'hoek' 25
 Variable 'onderdompeling' 120
  Lower bound variable 'onderdompeling' 50
  Upper bound variable 'onderdompeling' 250
 Variable 'versinkingsdiepte' 0.1
  Lower bound variable 'versinkingsdiepte' 0.1
  Upper bound variable 'versinkingsdiepte' 50
 Variable 'poorthoogte3D' 70
  Lower bound variable 'poorthoogte3D' 30
  Upper bound variable 'poorthoogte3D' 80
$
$ CONSTANTS
$
```

```
constants 3
 Constant 'wydte' 1575
 Constant 'gietspoed' 1000
 Constant 'pi' 3.14159
$
$ DEPENDENT VARIABLES
$
dependent 3
 Dependent 'inlaatsnelheid'
{(0.2*(wydte/1000)*(gietspoed/1000/60))/((pi/4)*0.115*0.115)}
 Dependent 'Dhidroulies' {(4*0.2*wydte/1000)/(2*((wydte/1000)+0.2))}
 Dependent 'SIgietspoed' {(gietspoed/1000/60)}

$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$      SOLVER "fluent"
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$
$ DEFINITION OF SOLVER "fluent"
$
 solver own 'fluent'
  solver command "/scratch/gideon/OPTIMERING1/fluent_script"
  solver input file "fluent.jou"
  prepro own
  prepro command "gambit -inp"
  prepro input file "/scratch/gideon/OPTIMERING1/gambitgen.jou"
  order linear
  experiment design dopt
  number experiments 8
  basis experiment 3toK
  concurrent jobs 1
$
$ RESPONSES FOR SOLVER "fluent"
$
 response 'turb_k_meniskus' 1 0 "cat maxwaarde.txt"
$
$ RESPONSE EXPRESSIONS FOR SOLVER "fluent"
$
 response 'geometrie_grens' {versinkingsdiepte + poorthoogte3D - 113}

$
$ OBJECTIVE FUNCTIONS
$
 objectives 1
 objective 'turb_k_meniskus' 1
$
$ CONSTRAINT DEFINITIONS
$
 constraints 1
  move
 constraint 'geometrie_grens'
  strict
  upper bound constraint 'geometrie_grens' 0
$
$ JOB INFO
$
 iterate param design 0.001
 iterate param objective 0.001
 iterate param stoppingtype and
 iterate 10
STOP
```

# APPENDIX M

## M. GAMBIT script file for 3D Old SEN design (for automatic geometry and mesh rendering)

### M.1 General

In order for one to later edit the GAMBIT script file, it is customary to make notes in the script file, which must obviously be ignored by the GAMBIT interpreter. Thus, all text in a line following a forward slash or "/", are notes and will be ignored.

*Exceptions and parameterisation:*

The script file (below in section M.2) may seem excessively long for creating a 3D geometry and mesh of a SEN and mould.

The reason for this is that certain exceptions may occur whenever the port angle vary from positive to negative (for example):

- different equations might be necessary
- different reference points are necessary to compute next positions

*Categories in typical GAMBIT script file*

The typical GAMBIT script file usually contains the following tasks in this specific order (exactly the same order in which a "manual" geometry and mesh would have been performed using GAMBIT's GUI):

1. List all parameters (and dependent[1] variables)
2. Build model

   2.1 Create outline of geometry based on given parameters

   2.2 Divide geometry into mesh-able areas and name areas (or volumes with a 3D model)

[1] Dependent variables are variables that need to be defined as their values are determined by the chosen parameters or design variables.

3. Mesh the geometry
4. Define and name all boundary surfaces

Refer to section M.2 on the following page for the GAMBIT script file used to generate 3D SEN (of the old type without a well) and mould models (quarter model due to assumption of symmetry). As mentioned in the main text, this GAMBIT script file (also known as a journal file) firstly creates a full model using elementary volumes, after which it is divided into quarters. Only the one quarter is kept to be exported as the mesh file for FLUENT.

## M.2 GAMBIT journal file for 3D SEN and mould (Old SEN design)

```
/ Journal File for GAMBIT 2.0.4 :meiparamsen3.jou
/ Weergawe 2002-05-09, 21:30

/ Verbetering op vorige teks-leer, nl  aprilparamsen2.jou , en ...
/ Journal File for GAMBIT 1.3.2: senkwartjetvolfyn.jou

/ Hierdie jou-leer maak ekstra volume om gietstuk-RVW in ag te kan neem

/ 1 Spesifisering van veranderlikes
/ $x1 = hoek van SENpoort met horisontaal in grade
/ $x2 = meniskusafstand vanaf onderpunt van SEN (funksie van x1 en x4) - word self
bereken
/ $x3 = wydte van gietstuk in mm
/ $x4 = afstand waarmee poort vergroot word in mm
/ $x5 = poortas afstand van onderkant van SEN af in mm (funksie van x1) - word self
bereken
/ $x6 = lengte van gietstuk in mm
/ $x7 = afwyking van die normale meniskusposisie (dus ondergedompelde diepte) in mm
/       [$x7 > 0 : dieper; daarteenoor as $x7 < 0 : vlakker]
$x1 = 15
$x3 = 1575
$x4 = 0
$x6 = 3000
$x7 = 0

/ 2 Begin van modelbou
volume create height 395 radius1 34 radius3 35 offset 0 0 197.5 zaxis frustum
vertex create coordinates 0 0 305
coordinate create cartesian oldsystem "c_sys.1" offset 0 0 305 axis1 "x" \
  angle1 0 axis2 "y" angle2 0 axis3 "z" angle3 0 rotation
coordinate activate "c_sys.1"
volume create height 305 radius1 51.5 radius3 61 offset 0 0 152.5 zaxis frustum
coordinate activate "c_sys.2"
volume create height 90 radius1 61 radius3 69.5 offset 0 0 45 zaxis frustum
coordinate create cartesian oldsystem "c_sys.2" offset 0 0 90 axis1 "x" \
  angle1 0 axis2 "y" angle2 0 axis3 "z" angle3 0 rotation
vertex create coordinates 85 0 0
vertex create coordinates 69.5 0 40
vertex create coordinates 0 0 40
edge create radius 50 startangle -90 endangle 0 center "vertex.8" zxplane arc
edge create straight "vertex.10" "vertex.9"
edge split "edge.7" parameter 0.590333 connected
edge delete "edge.9" "edge.8" lowertopology
vertex create coordinates 69.5 0 40
edge create straight "vertex.14" "vertex.13"
edge create straight "vertex.14" "vertex.6"
edge create straight "vertex.6" "vertex.1"
face create wireframe "edge.7" "edge.8" "edge.9" "edge.10" real
vertex delete "vertex.8"
volume create revolve "face.10" dangle 360 vector 0 0 1 origin 0 0 0 draft 0 \
  extended
coordinate activate "c_sys.1"
volume create height 530 radius1 32.5 radius3 34 offset 0 0 -265 zaxis frustum
volume create height 530 radius1 48.2 radius3 51.5 offset 0 0 -265 zaxis frustum
volume create height 530 sides 4 radius1 31.81980515 radius2 70 radius3 \
  48.08326112 offset 0 0 -265 zaxis pyramid
volume intersect volumes "volume.7" "volume.5"
volume create height 530 sides 4 radius1 54.44722215 radius2 85 radius3 \
  72.83199846 offset 0 0 -265 zaxis pyramid
volume intersect volumes "volume.8" "volume.6"
/ File closed at Mon Nov 12 11:48:36 2001, 9.47 cpu second(s), 3141768 maximum memory.
coordinate delete "c_sys.3" "c_sys.2"
vertex delete "vertex.3"
volume create translate "face.39" vector 0 0 -135
volume create translate "face.29" vector 0 0 -70
coordinate create cartesian oldsystem "c_sys.1" offset 0 0 -665 axis1 "x" \
  angle1 0 axis2 "y" angle2 0 axis3 "z" angle3 0 rotation

////////////////////////////////////////////////
/ Hoek word hier verander
/ $x5 = poortas (voor verlenging) van onder af in mm - word vervolgens bereken
```

```
/ As hoek 0 is, maak effense positiewe hoek anders faal jou-leer
IF COND ($x1 .EQ. 0)
$x1 = 0.1
ENDIF

/ As hoek positief is, gebruik eerste vergelyking; andersins tweede een
IF COND ($x1 .GT. 0)
$x5 = 17.00446417 + 35/(cos($x1))
/ As hoek negatief is
ELSE
$x5 = 17.00446417 + 35/(cos($x1)) + 48.5*tan(-$x1)
ENDIF

coordinate create cartesian oldsystem "c_sys.2" offset 0 0 $x5 \
  axis1 "x" angle1 $x1 axis2 "y" angle2 0 axis3 "z" angle3 0 rotation
/////////////////////////////////////////////////

volume create height 100 radius1 35 radius3 35 offset 0 50 0 yaxis frustum
volume create height 100 sides 4 radius1 70 radius2 31.81980515 radius3 70 \
  offset 0 50 0 yaxis pyramid
volume intersect volumes "volume.12" "volume.11"
volume create translate "face.62" vector 0 -30 -4.82965e-11
volume unite volumes "volume.12" "volume.13"
coordinate create cartesian oldsystem "c_sys.3" offset 0 -40 0 axis1 "x" \
  angle1 0 axis2 "y" angle2 0 axis3 "z" angle3 0 rotation
volume create width 100 depth 150 height 100 offset 50 75 -50 brick
volume create width 100 depth 150 height 100 offset -50 75 -50 brick
volume unite volumes "volume.14" "volume.13"
volume intersect volumes "volume.14" "volume.12" keeporiginals
volume delete "volume.14" lowertopology
volume subtract "volume.12" volumes "volume.15" keeptool

/////////////////////////////////////////////////
/ Poort word hier vergroot

/ As poort met 0 vergroot word, maak dit 0.1 anders faal jou-leer
IF COND ($x4 .EQ. 0)
$x4 = 0.1
ENDIF

volume move "volume.12" offset 0 0 $x4
volume create translate "face.92" vector 0 7.451e-12 $x4
/////////////////////////////////////////////////

volume unite volumes "volume.12" "volume.16" "volume.15"
coordinate activate "c_sys.2"
volume create width 100 depth 100 height 200 offset -50 -50 100 brick
volume create width 100 depth 100 height 200 offset 50 -50 100 brick
volume unite volumes "volume.13" "volume.14"
volume subtract "volume.12" volumes "volume.13"
volume copy "volume.12" to "volume.13"
volume reflect "volume.13" vector 0 1 0 origin 0 0 0
volume unite volumes "volume.12" "volume.13"
volume intersect volumes "volume.12" "volume.9" keeporiginals
volume unite volumes "volume.13" "volume.10"
volume delete "volume.12" lowertopology
volume subtract "volume.9" volumes "volume.13" keeptool
coordinate delete "c_sys.3" "c_sys.4"
face create wireframe "edge.12" real
volume create stitch "face.148" "face.11" "face.1" real
volume create stitch "face.1" "face.3" "face.2" real

///////////////////////////////////////
/ $x2 = meniskus z-posisie t.o.v. onderkant van SEN in mm
/ $x3 = wydte van gietstuk
/ Berekening van meniskushoogte verskil afhangend of die hoek x1 positief of negatief
is

IF COND ($x1 .GT. 0)
$x2 = 17.00446417 + 70/cos($x1) + $x4/cos($x1) + 48.5*tan($x1) + 120 + $x7
ELSE
$x2 = 17.00446417 + 70/cos($x1) + $x4/cos($x1) + 120 +$x7
ENDIF

coordinate create "meniskusas" cartesian oldsystem "c_sys.2" offset 0 0 \
  $x2 axis1 "x" angle1 0 axis2 "y" angle2 0 axis3 "z" angle3 0 rotation
```

```
face create "meniskus" width 200 height $x3 xyplane rectangle
////////////////////////////////////////

 / lengte van gietstuk hier
volume create "gietstuk" translate "meniskus" vector 0 0 -$x6
//////////////////////////

volume subtract "volume.3" volumes "volume.1" keeptool
volume subtract "volume.2" volumes "volume.21" keeptool
volume intersect volumes "gietstuk" "volume.15" keeporiginals
volume subtract "volume.22" volumes "volume.14" keeptool
volume delete "volume.19" "volume.3" "volume.2" "volume.15" lowertopology

 / maak nou 'n kwartmodel
volume create "bo" width 110 depth 800 height 1110 offset 55 400 555 brick
volume create "onder" width 110 depth 800 height 4500 offset 55 400 -2250 brick
volume unite volumes "onder" "bo"

volume intersect volumes "onder" "volume.20" keeporiginals
volume intersect volumes "onder" "volume.21" keeporiginals
volume intersect volumes "onder" "volume.14" keeporiginals
volume intersect volumes "onder" "volume.22" keeporiginals
volume intersect volumes "onder" "volume.9" keeporiginals
volume intersect volumes "onder" "volume.13" keeporiginals
volume intersect volumes "onder" "gietstuk" keeporiginals
volume delete "onder" "volume.20" "volume.21" "volume.14" "volume.22" \
  "volume.9" "volume.13" lowertopology
volume delete "gietstuk" lowertopology
volume subtract "volume.31" volumes "volume.28" "volume.27" "volume.29" \
  "volume.30" keeptool
volume delete "volume.31"
face subtract "face.335" faces "face.296" keeptool
volume create stitch "face.305" "face.316" "face.351" "face.352" "face.310" \
  "face.315" "face.246" "face.245" "face.338" "face.335" "face.296" \
  "face.275" real
volume modify "volume.25" label "tuit"
volume modify "volume.26" label "rgtskag"
volume modify "volume.27" label "morfdeel"
volume modify "volume.30" label "SENpoort"
volume modify "volume.31" label "gietstuk"
volume delete "volume.28" "volume.29" lowertopology

 / heg los vlakke aan mekaar
face connect "face.201" "face.215" real
face connect "face.232" "face.218" real
face connect "face.230" "face.299" real
/ einde van model


/3 Aanpassings vir jetvolume voor meshing begin
coordinate create "jetvolas" cartesian oldsystem "meniskusas" offset 0 0 -450 \
  axis1 "x" angle1 0 axis2 "y" angle2 0 axis3 "z" angle3 0 rotation
volume create "tydelikonder" width 250 depth 1000 height 4000 offset 125 500 \
  -2000 brick
volume intersect volumes "gietstuk" "tydelikonder" keeporiginals
volume subtract "gietstuk" volumes "volume.33" keeptool
volume delete "tydelikonder" lowertopology
volume modify "volume.33" label "gietstukonder"
volume modify "gietstuk" label "jetvolume"
face connect "face.380" "face.377" real

/32 Addisionele aanpassings vir ekstra volume vir maasvereenvoudiging
coordinate activate "c_sys.2"
coordinate create "meshvolas" cartesian oldsystem "c_sys.2" offset 0 0 -100 \
  axis1 "x" angle1 0 axis2 "y" angle2 0 axis3 "z" angle3 0 rotation
volume create "meshvol" width 110 depth 180 height 450 offset 55 90 225 brick
volume intersect volumes "jetvolume" "meshvol" keeporiginals
volume delete "meshvol" lowertopology
volume subtract "jetvolume" volumes "volume.35" keeptool
volume modify "volume.35" label "meshvol"
face delete "face.321" "face.322" "face.339"
face connect "face.410" "face.416" real
face connect "face.412" "face.415" real
face connect "face.399" "face.296" real

/33 Addisionele aanpassings vir ekstra volume vir gietstuk-RVW
```

```
volume create "gietstukvol" translate "face.380" vector 0 0 -250
volume subtract "gietstukonder" volumes "gietstukvol" keeptool
volume modify "volume.37" label "gietstukvol"
volume modify "volume.38" label "jetvolume"


/4 Begin met Meshing
solver select "FLUENT 5/6"

/ 41 Mesh gietstuk
/voorbereiding en mesh vir jetvolume, gietstukvol se mesh
edge picklink "edge.847" "edge.850" "edge.907" "edge.902" "edge.911" \
  "edge.666"
edge mesh "edge.666" "edge.911" "edge.902" "edge.907" "edge.850" "edge.847" \
  successive ratio1 1 size 5
edge picklink "edge.977" "edge.975"
edge mesh "edge.975" "edge.977" successive ratio1 1 size 5
volume mesh "jetvolume" submap size 15
volume mesh "gietstukvol" map size 15


/ 42 Mesh meshvol
sfunction create "SENpoortbron" sourcefaces "face.399" startsize 4 growthrate 1.1 \
  distance 50 sizelimit 10 attachvolumes "meshvol" fixed
volume mesh "meshvol" tetrahedral size 10

/ 43 Mesh SENpoort, tuit, rgtskag en morfdeel
volume modify "volume.36" label "SENpoort"
volume mesh "SENpoort" tetrahedral size 4
volume mesh "tuit" cooper source "face.204" "face.201" size 5
volume mesh "rgtskag" cooper source "face.232" "face.201" size 5
volume mesh "morfdeel" tetrahedral size 4

/44 Mesh onder gietstuk
edge modify "edge.785" backward
edge picklink "edge.785"
edge modify "edge.785" successive ratio1 1 size 1
edge mesh "edge.978" "edge.785" "edge.980" "edge.979" firstlength ratio1 15 \
  size 25.5
volume mesh "gietstukonder" map size 15

/45 Vee uit ekstra edges
edge delete "edge.509" "edge.511" "edge.513" "edge.522" "edge.527" "edge.591" \
"edge.694" "edge.726" "edge.733" "edge.756" "edge.761"

/5 Vir Fluent: Randvoorwaardes (defini-ering van vlakke)
physics create "SENinlaat" btype "VELOCITY_INLET" face "face.204"
physics create "gietstuk_uitlaat" btype "PRESSURE_OUTLET" face "face.367"
physics create "SENmuur_buite" btype "WALL" face "face.217" "face.216" "face.202" \
  "face.229" "face.233"
physics create "SENmuur_binne" btype "WALL" face "face.402" "face.398" "face.401" \
  "face.400" "face.405"
physics create "SENpoortmuur_binne" btype "WALL" face "face.290" "face.300" \
  "face.295" "face.301"
physics create "gietstukmuur_nou" btype "WALL" face "face.310" "face.433"
physics create "gietstukmuur_wyd" btype "WALL" face "face.386" "face.396" \
  "face.430"
physics create "ondermould_wyd" btype "WALL" face "face.366"
physics create "ondermould_nou" btype "WALL" face "face.378"
physics create "simmetrie_nou" btype "SYMMETRY" face "face.197" "face.208" \
  "face.234" "face.302" "face.395" "face.427" "face.431" "face.441"
physics create "simmetrie_wyd" btype "SYMMETRY" face "face.205" "face.219" \
  "face.223" "face.413" "face.285" "face.352" "face.432" "face.440"
physics create "meniskusvlak" btype "WALL" face "face.428" "face.414"
physics create "meshvolvlak1" btype "INTERIOR" face "face.410"
physics create "meshvolvlak2" btype "INTERIOR" face "face.412"
physics create "binnemould_vlak" btype "INTERIOR" face "face.380"
physics create "ondermould_vlak" btype "INTERIOR" face "face.438"
physics create "SENpoortuitlaat" btype "INTERIOR" face "face.399"

/ File closed at Tue Apr 16 17:12:45 2002, 13215.00 cpu second(s), 79360040 maximum
memory.
```

# APPENDIX N

## N. Summary: CFD results of 3D design exploration

### N.1 CFD set-up data

The CFD set-up data is repeated here very briefly for the sake of completeness:

- Liquid steel properties used for temperature on settings
- Turbulence model: k-ω standard
- Dynamic grid adaption employed: based on velocity gradients as adaption criterion
- Initial grid size: 500 000 cells; Final grid size: approximately 800 000 cells
- First-order discretisation schemes followed by second-order discretisation

### N.2 Experimental designs

The experiments used for the 3D exploration study are presented in Table N.1 below. The relevant Figure numbers are also shown in Table N.1.

Firstly, the constant operational parameters (constant for all results in this Appendix) will be listed below:

- Submergence depth: 80mm (regarded as a worst case)
- Casting speed (directly proportional to flow rate through CFD models): 1.3 m/min
- Mould width: 1060mm and 1250mm for each SEN design type

Table N.1: Experiments in central-composite design, including base case (experiment 1.0) and linear and quadratic optima fits by LS-OPT

| **Figure N._** | **Experiment designation** | **SEN port angle [º]** | **SEN port height [mm]** | **SEN well depth [mm]** |
|---|---|---|---|---|
| 2 | 1.0 | 15 | 70 | 1 ≈ 0 |
| 3 | 1.1 | 0 | 55 | 20 |
| 4 | 1.2 | 7.9 | 69.9 | 32.1 |
| 5 | 1.3 | -12.9 | 69.9 | 32.1 |
| 6 | 1.4 | 7.9 | 40.1 | 32.1 |
| 7 | 1.5 | -12.9 | 40.1 | 32.1 |
| 8 | 1.6 | 7.9 | 69.9 | 8.9 |
| 9 | 1.7 | -12.9 | 69.9 | 8.9 |
| 10 | 1.8 | 7.9 | 40.1 | 8.9 |
| 11 | 1.9 | -12.9 | 40.1 | 8.9 |
| 12 | 1.10 | -2.5 | 55 | 20.5 |
| 13 | 1.11 | 15 | 55 | 20.5 |
| 14 | 1.12 | -2.5 | 80 | 20.5 |
| 15 | 1.13 | -2.5 | 55 | 40 |
| 16 | 1.14 | -20 | 55 | 20.5 |
| 17 | 1.15 | -2.5 | 30 | 20.5 |
| 18 | 1.16 | -2.5 | 55 | 1 |
| 19 | 2.0_linear | -20 | 80 | 1 |
| 20 | 2.0_quadratic | -20 | 55.56 | 40 |

## N.3 <u>Summary results data</u>

After each CFD model evaluation, the maximum TKE and the maximum velocity on the meniscus surface (averaged over the last 5000 iterations), are calculated using the post-processing capabilities of FLUENT. These values are listed in Table N.2 below, and will be used to determine the multi-objective values for each experimental design (and optima predicted by LS-OPT).

Table N.2: Summary Results data: maximum TKE and maximum velocity on meniscus of each SEN design for both widths (1060 and 1250mm)

| **Experiment designation** | **1060 mm width** | | **1250 mm width** | |
|---|---|---|---|---|
| | **Maximum velocity [m/s]** | **Maximum TKE [$m^2/s^2$]** | **Maximum velocity [m/s]** | **Maximum TKE [$m^2/s^2$]** |
| 1.0 | 3.87E-01 | 2.55E-03 | 3.98E-01 | 1.33E-03 |
| 1.1 | 4.63E-01 | 2.61E-03 | 5.34E-01 | 4.37E-03 |
| 1.2 | 4.68E-01 | 2.09E-03 | 5.88E-01 | 3.84E-03 |
| 1.3 | 5.23E-01 | 4.14E-03 | 5.16E-01 | 5.95E-03 |
| 1.4 | 5.54E-01 | 9.98E-03 | 5.44E-01 | 9.43E-03 |
| 1.5 | 4.36E-01 | 2.42E-03 | 5.88E-01 | 4.25E-03 |
| 1.6 | 5.49E-01 | 5.58E-03 | 5.90E-01 | 6.10E-03 |
| 1.7 | 3.39E-01 | 2.35E-03 | 4.84E-01 | 1.90E-03 |
| 1.8 | 3.13E-01 | 5.34E-03 | 4.84E-01 | 9.53E-03 |
| 1.9 | 4.06E-01 | 2.22E-03 | 6.95E-01 | 9.88E-03 |
| 1.10 | 4.92E-01 | 3.16E-03 | 6.86E-01 | 6.20E-03 |
| 1.11 | 4.49E-01 | 2.75E-03 | 4.97E-01 | 2.43E-03 |
| 1.12 | 4.82E-01 | 3.24E-03 | 5.80E-01 | 6.90E-03 |
| 1.13 | 4.71E-01 | 2.86E-03 | 5.44E-01 | 3.05E-03 |
| 1.14 | 3.83E-01 | 3.10E-03 | 5.46E-01 | 4.69E-03 |
| 1.15 | 5.72E-01 | 6.77E-03 | 6.00E-01 | 9.72E-03 |
| 1.16 | 5.55E-01 | 4.11E-03 | 6.07E-01 | 4.53E-03 |
| 2.0_linear | 2.63E-01 | 1.47E-03 | 4.45E-01 | 2.24E-03 |
| 2.0_quadratic | 3.70E-01 | 3.21E-03 | 4.21E-01 | 2.17E-03 |

The values tabulated in Table N.2 are depicted graphically in Figure N.1 below:

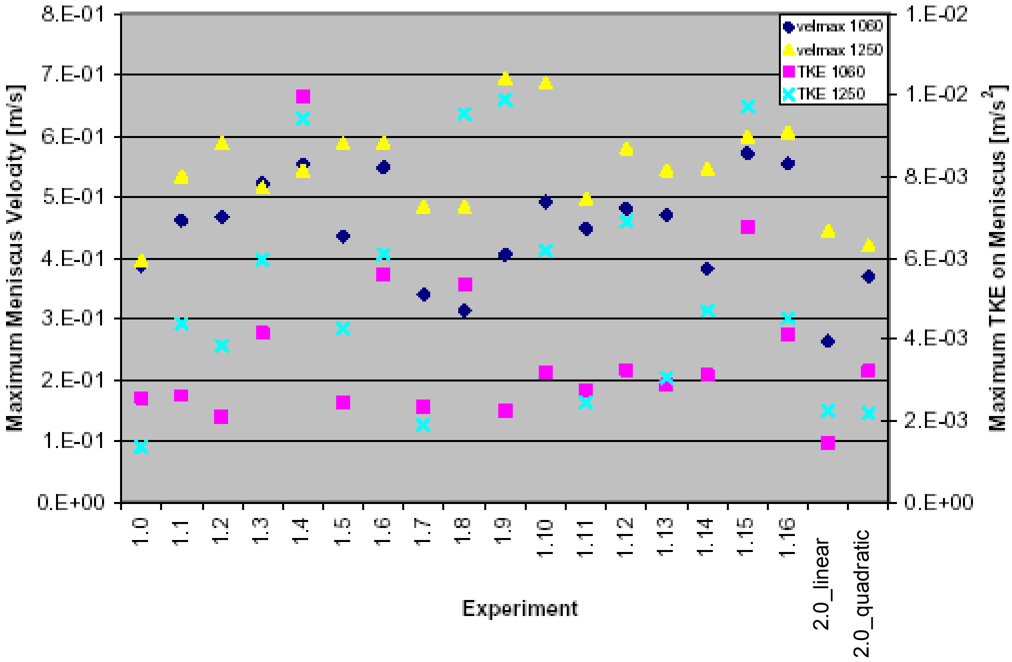



Figure N.1: Graphical display of data in Table N.2

The multi-objective values that are calculated from the data in Table N.2 and Figure N.1 above are displayed in the main text (Chapter 5) in Figure 5.17.

The velocity contours on the centre plane of each design follows in section N.4.

## N.4 CFD Results: velocity contours of magnitude on centre plane (last iterations)

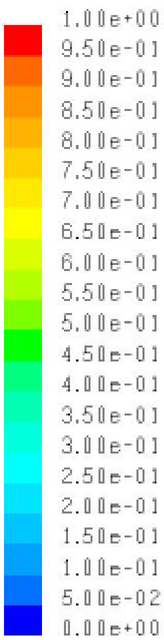
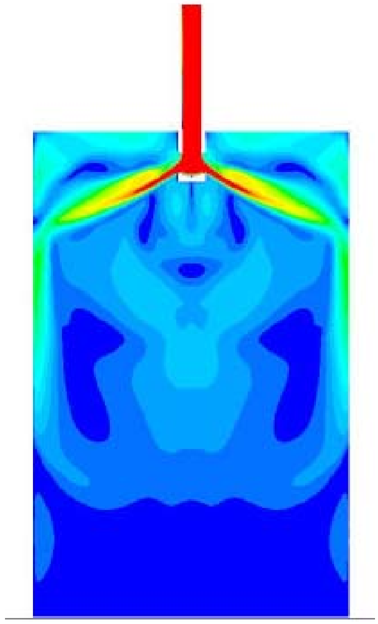
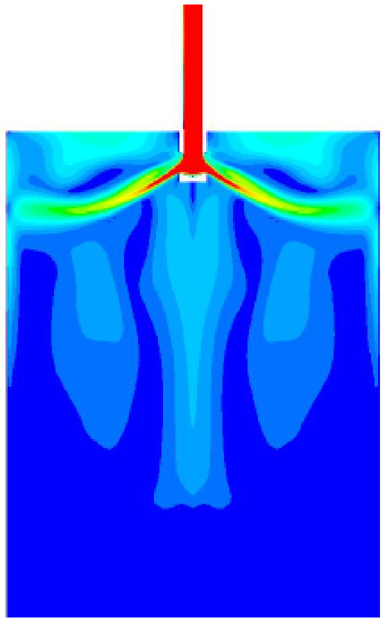
| **Experiment designation** | **Velocity scale [0 – 1 m/s]** | **1060mm width (80mm submergence; 1.3 m/min)** | **1250mm width (80mm submergence; 1.3 m/min)** |
|---|---|---|---|
| **1.0**<br>• angle<br>• port height<br>• well depth<br>• 15º (up)<br>• 70mm<br>• 0mm |  |  |  |

Figure N.2: Experiment 1.0 contours of velocity magnitude on centre plane (range 0 – 1 m/s)

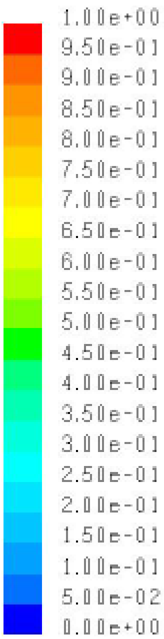
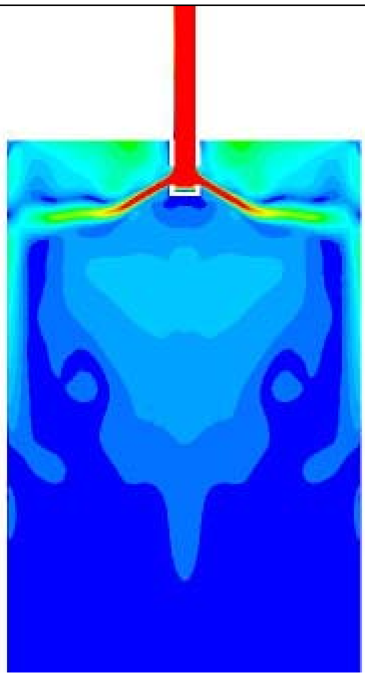
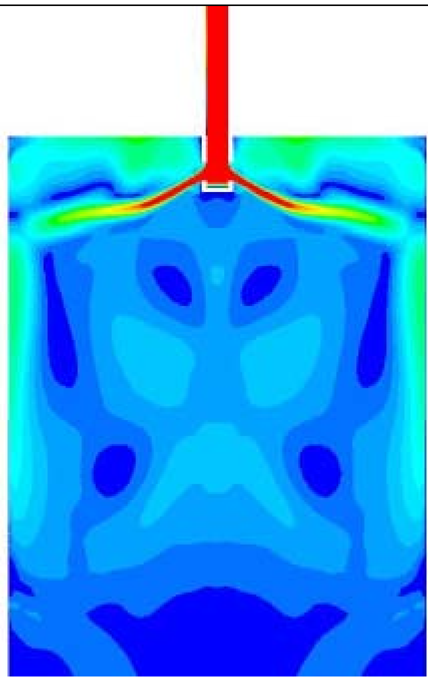
| **Experiment designation** | **Velocity scale [0 – 1 m/s]** | **1060mm width (80mm submergence; 1.3 m/min)** | **1250mm width (80mm submergence; 1.3 m/min)** |
|---|---|---|---|
| **1.1**<br>• angle<br>• port height<br>• well depth<br>• 0º<br>• 55mm<br>• 20mm |  |  |  |

Figure N.3: Experiment 1.1 contours of velocity magnitude on centre plane (range 0 – 1 m/s)

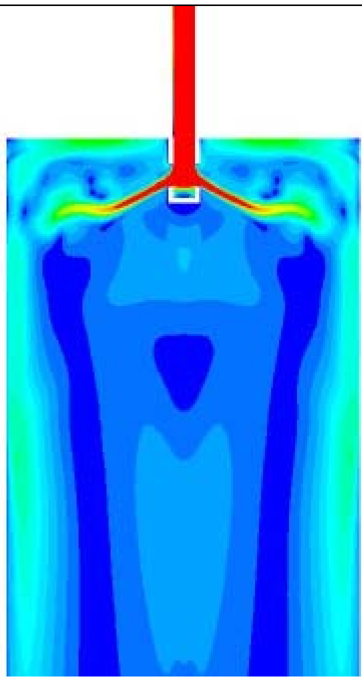
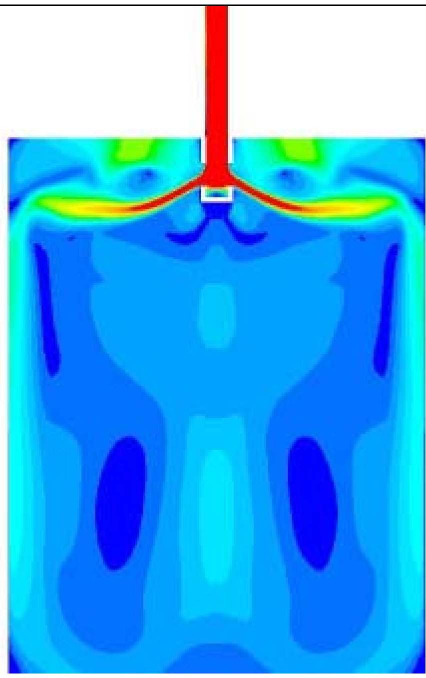
| Experiment designation | Velocity scale [0 – 1 m/s] | **1060mm width** (80mm submergence; 1.3 m/min) | **1250mm width** (80mm submergence; 1.3 m/min) |
|---|---|---|---|
| **1.2**<br>• angle<br>• port height<br>• well depth<br><br>• 7.9°<br>• 69.9mm<br>• 32.1mm |  |  |  |

Figure N.4: Experiment 1.2 contours of velocity magnitude on centre plane (range 0 – 1 m/s)

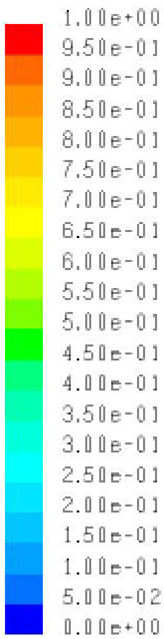
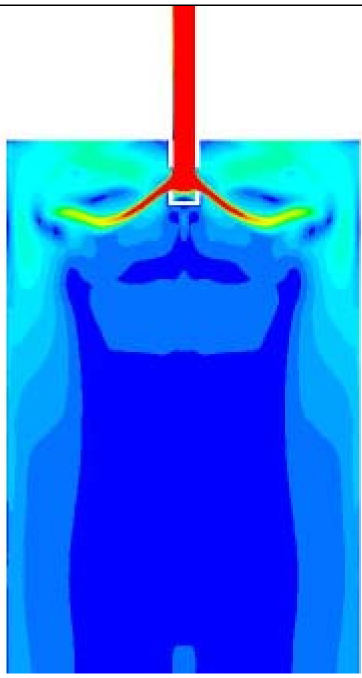
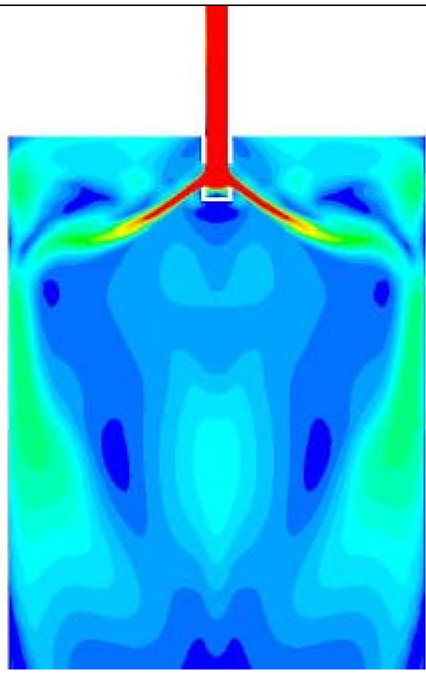
| Experiment designation | Velocity scale [0 – 1 m/s] | **1060mm width** (80mm submergence; 1.3 m/min) | **1250mm width** (80mm submergence; 1.3 m/min) |
|---|---|---|---|
| **1.3**<br>• angle<br>• port height<br>• well depth<br><br>• -12.9°<br>• 69.9mm<br>• 32.1mm |  |  |  |

Figure N.5: Experiment 1.3 contours of velocity magnitude on centre plane (range 0 – 1 m/s)

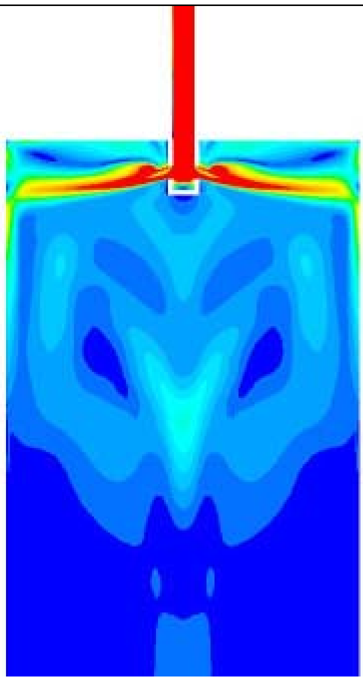
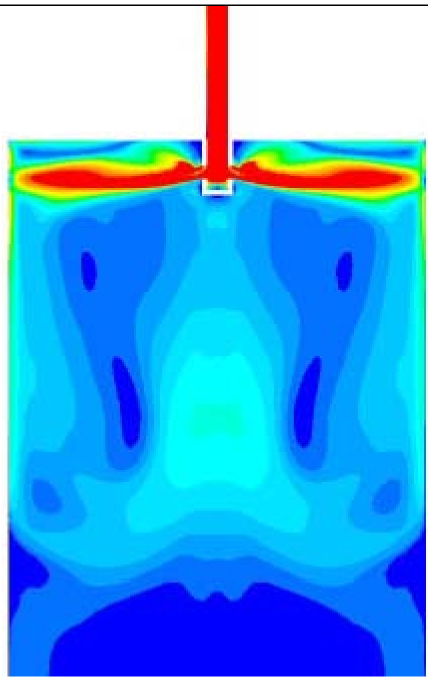
| **Experiment designation** | **Velocity scale [0 – 1 m/s]** | **1060mm width (80mm submergence; 1.3 m/min)** | **1250mm width (80mm submergence; 1.3 m/min)** |
|---|---|---|---|
| **1.4**<br>• angle<br>• port height<br>• well depth<br>• 7.9°<br>• 40.1mm<br>• 32.1mm |  |  |  |

Figure N.6: Experiment 1.4 contours of velocity magnitude on centre plane (range 0 – 1 m/s)

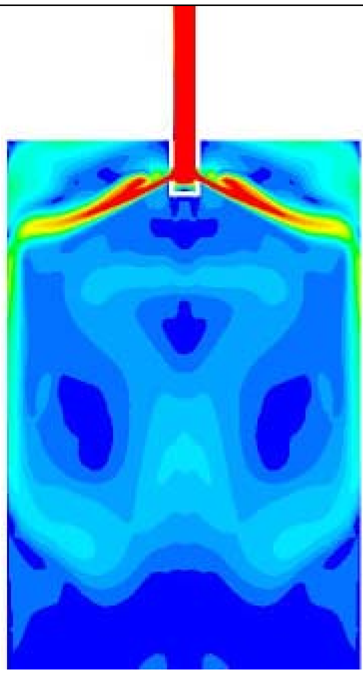
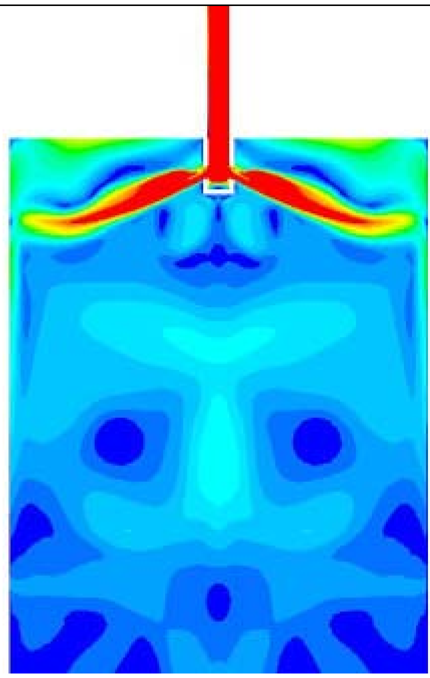
| **Experiment designation** | **Velocity scale [0 – 1 m/s]** | **1060mm width (80mm submergence; 1.3 m/min)** | **1250mm width (80mm submergence; 1.3 m/min)** |
|---|---|---|---|
| **1.5**<br>• angle<br>• port height<br>• well depth<br>• -12.9°<br>• 40.1mm<br>• 32.1mm |  |  |  |

Figure N.7: Experiment 1.5 contours of velocity magnitude on centre plane (range 0 – 1 m/s)

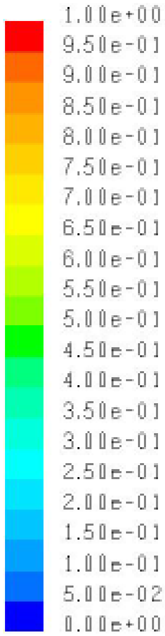
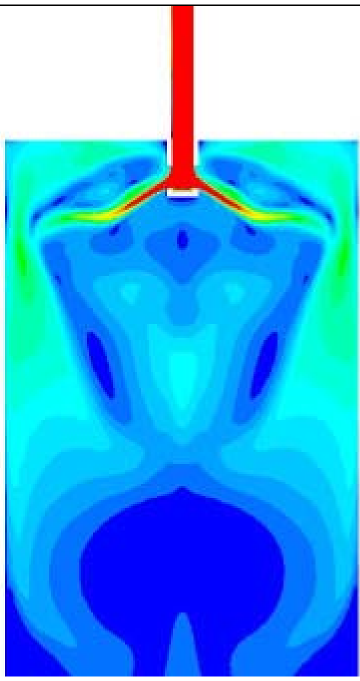
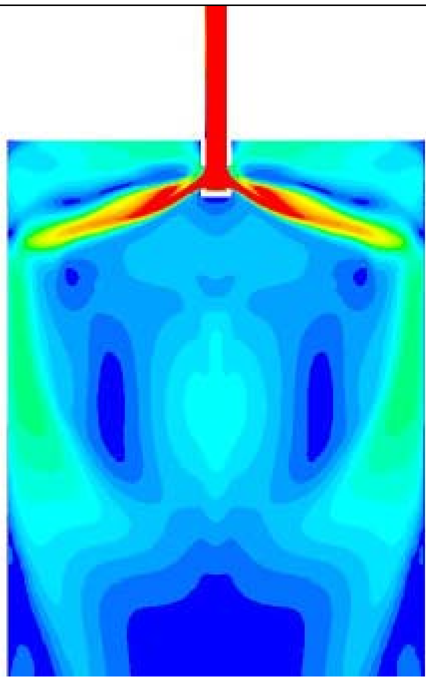
| Experiment designation | Velocity scale [0 – 1 m/s] | **1060mm** width (80mm submergence; 1.3 m/min) | **1250mm** width (80mm submergence; 1.3 m/min) |
|---|---|---|---|
| **1.6**<br>• angle<br>• port height<br>• well depth<br>• 7.9°<br>• 69.9mm<br>• 8.9mm |  |  |  |

Figure N.8: Experiment 1.6 contours of velocity magnitude on centre plane (range 0 – 1 m/s)

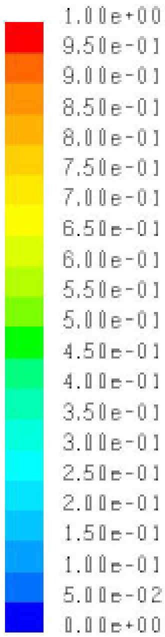
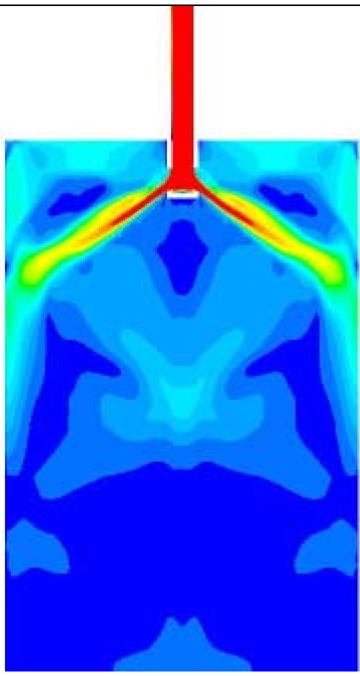
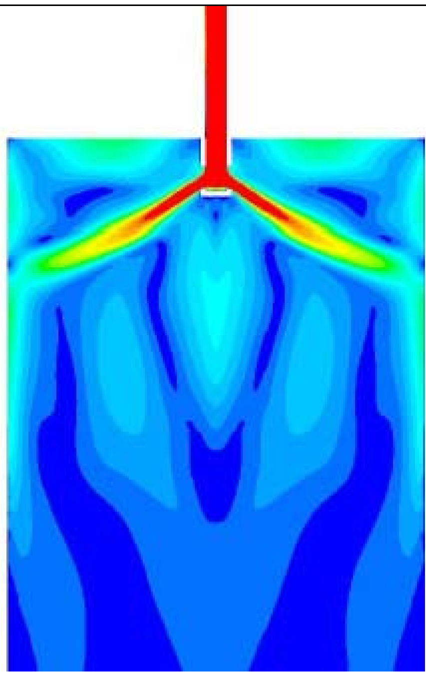
| Experiment designation | Velocity scale [0 – 1 m/s] | **1060mm** width (80mm submergence; 1.3 m/min) | **1250mm** width (80mm submergence; 1.3 m/min) |
|---|---|---|---|
| **1.7**<br>• angle<br>• port height<br>• well depth<br>• -12.9°<br>• 69.9mm<br>• 8.9mm |  |  |  |

Figure N.9: Experiment 1.7 contours of velocity magnitude on centre plane (range 0 – 1 m/s)

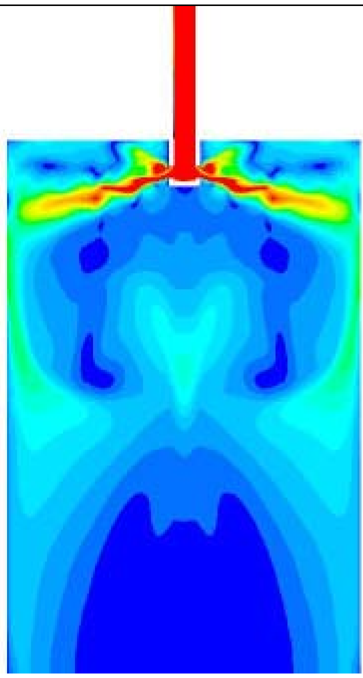
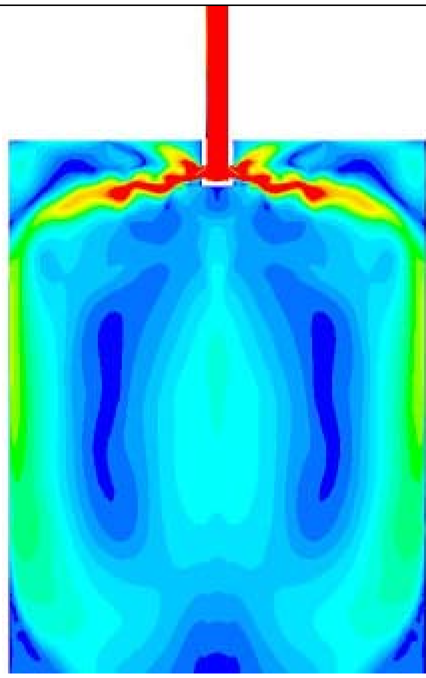
| **Experiment designation** | **Velocity scale [0 – 1 m/s]** | **1060mm width (80mm submergence; 1.3 m/min)** | **1250mm width (80mm submergence; 1.3 m/min)** |
|---|---|---|---|
| **1.8**<br><br>• angle<br>• port height<br>• well depth<br><br>• 7.9°<br>• 40.1mm<br>• 8.9mm |  |  |  |

Figure N.10: Experiment 1.8 contours of velocity magnitude on centre plane (range 0 – 1 m/s)

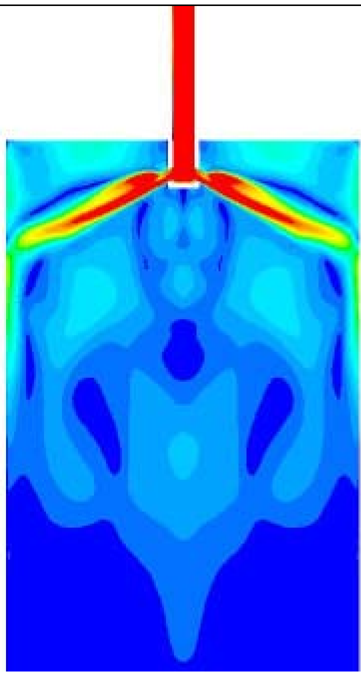
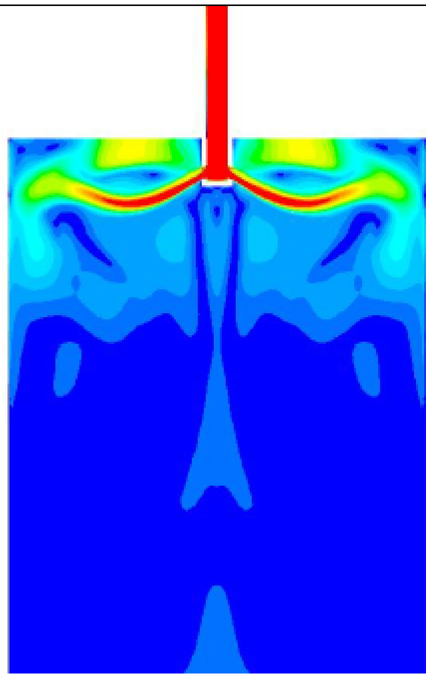
| **Experiment designation** | **Velocity scale [0 – 1 m/s]** | **1060mm width (80mm submergence; 1.3 m/min)** | **1250mm width (80mm submergence; 1.3 m/min)** |
|---|---|---|---|
| **1.9**<br><br>• angle<br>• port height<br>• well depth<br><br>• -12.9°<br>• 40.1mm<br>• 8.9mm |  |  |  |

Figure N.11: Experiment 1.9 contours of velocity magnitude on centre plane (range 0 – 1 m/s)

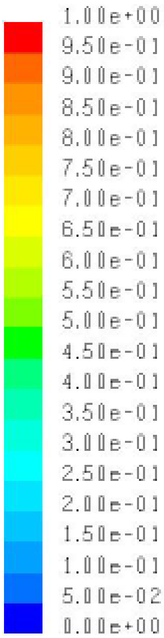
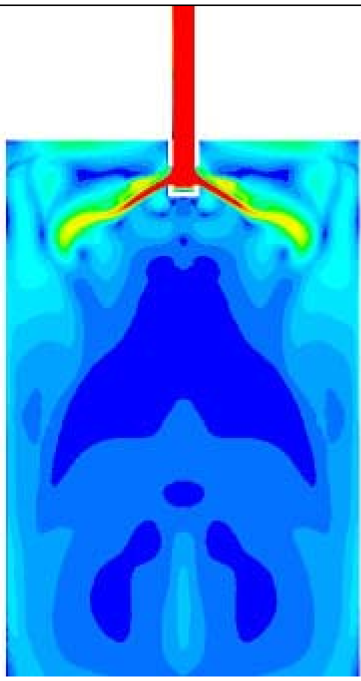
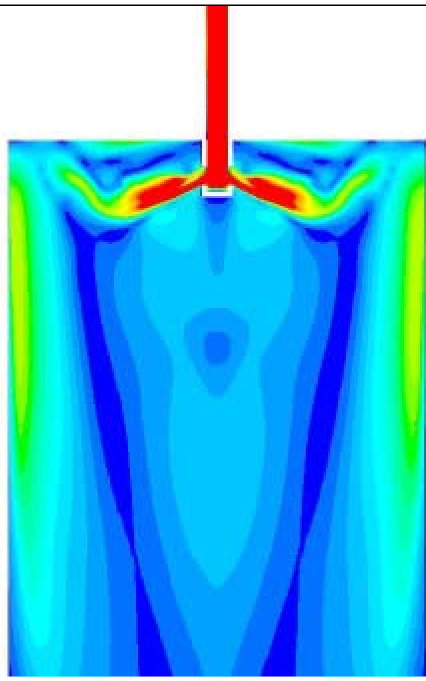
| **Experiment designation** | **Velocity scale [0 – 1 m/s]** | **1060mm width (80mm submergence; 1.3 m/min)** | **1250mm width (80mm submergence; 1.3 m/min)** |
|---|---|---|---|
| **1.10**<br>• angle<br>• port height<br>• well depth<br>• -2.5°<br>• 55mm<br>• 20.5mm |  |  |  |

Figure N.12: Experiment 1.10 contours of velocity magnitude on centre plane (range 0 – 1 m/s)

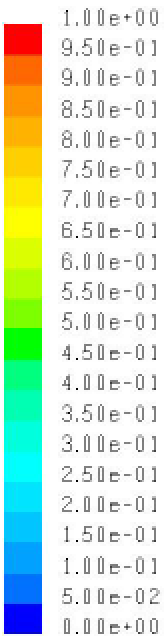
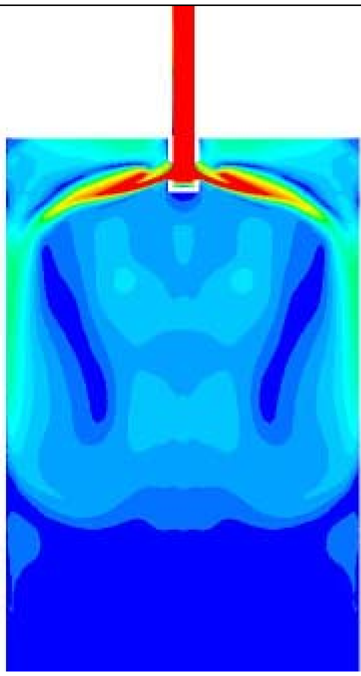
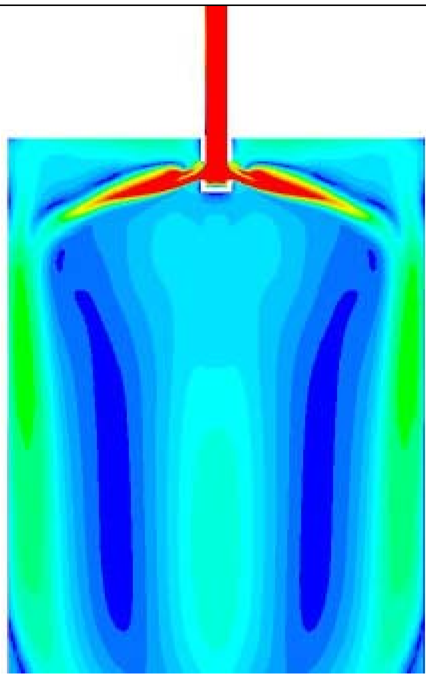
| **Experiment designation** | **Velocity scale [0 – 1 m/s]** | **1060mm width (80mm submergence; 1.3 m/min)** | **1250mm width (80mm submergence; 1.3 m/min)** |
|---|---|---|---|
| **1.11**<br>• angle<br>• port height<br>• well depth<br>• 15°<br>• 55mm<br>• 20.5mm |  |  |  |

Figure N.13: Experiment 1.11 contours of velocity magnitude on centre plane (range 0 – 1 m/s)

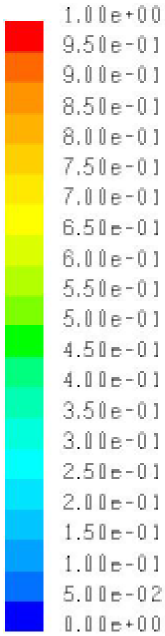
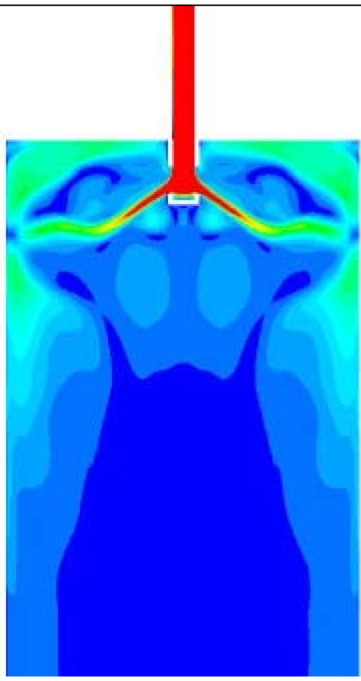
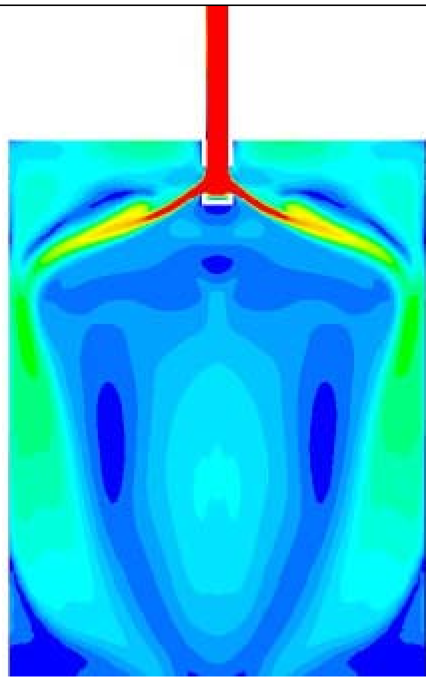
| Experiment designation | Velocity scale [0 – 1 m/s] | **1060mm** width (80mm submergence; 1.3 m/min) | **1250mm** width (80mm submergence; 1.3 m/min) |
|---|---|---|---|
| **1.12**<br>• angle<br>• port height<br>• well depth<br><br>• -2.5°<br>• 80mm<br>• 20.5mm |  |  |  |

Figure N.14: Experiment 1.12 contours of velocity magnitude on centre plane (range 0 – 1 m/s)

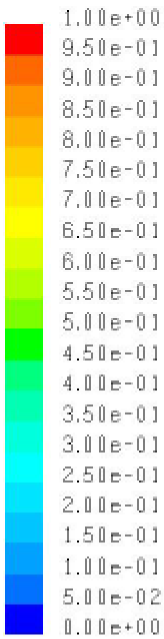
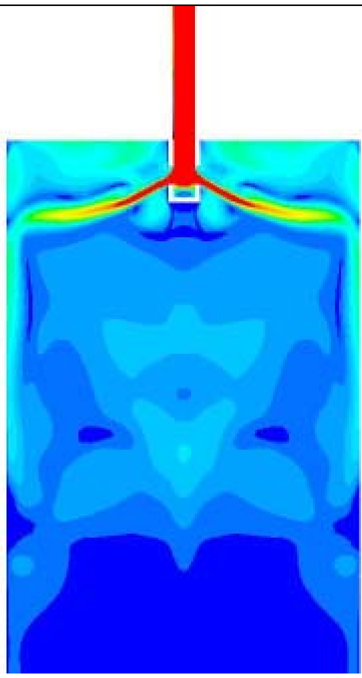
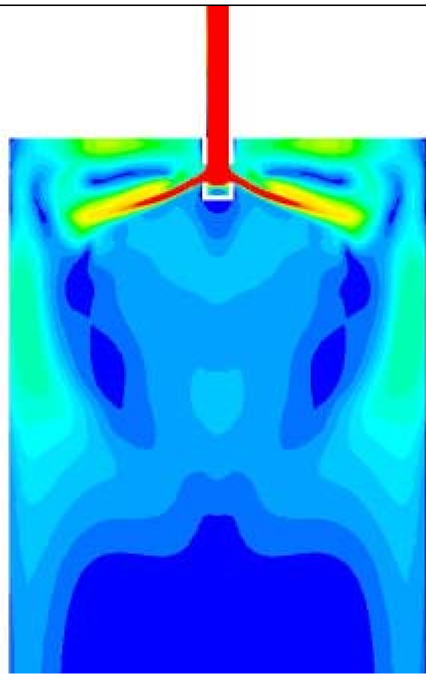
| Experiment designation | Velocity scale [0 – 1 m/s] | **1060mm** width (80mm submergence; 1.3 m/min) | **1250mm** width (80mm submergence; 1.3 m/min) |
|---|---|---|---|
| **1.13**<br>• angle<br>• port height<br>• well depth<br><br>• -2.5°<br>• 55mm<br>• 40mm |  |  |  |

Figure N.15: Experiment 1.13 contours of velocity magnitude on centre plane (range 0 – 1 m/s)

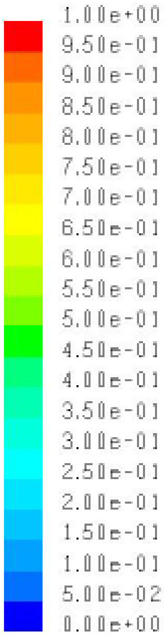
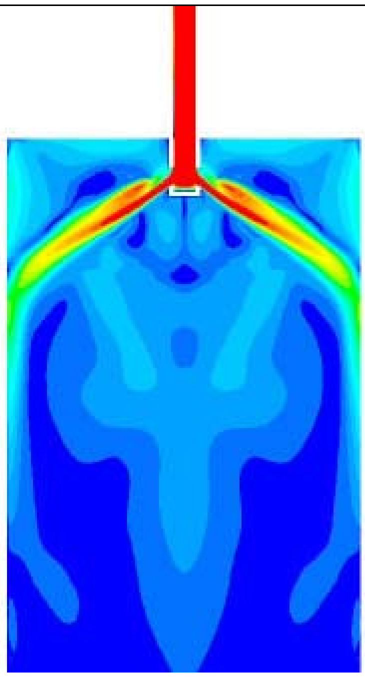
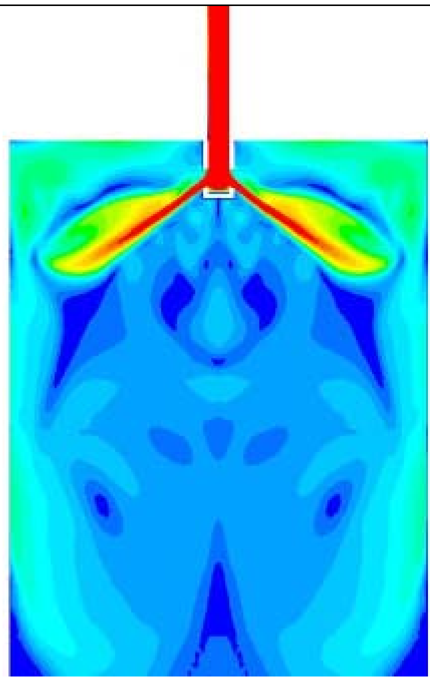
| Experiment designation | Velocity scale [0 – 1 m/s] | **1060mm** width (80mm submergence; 1.3 m/min) | **1250mm** width (80mm submergence; 1.3 m/min) |
|---|---|---|---|
| **1.14**<br>• angle<br>• port height<br>• well depth<br><br>• -20°<br>• 55mm<br>• 20.5mm |  |  |  |

Figure N.16: Experiment 1.14 contours of velocity magnitude on centre plane (range 0 – 1 m/s)

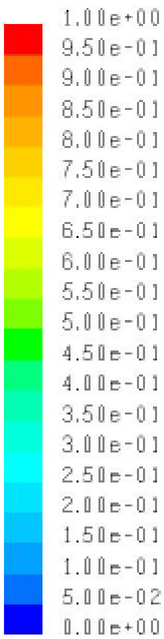
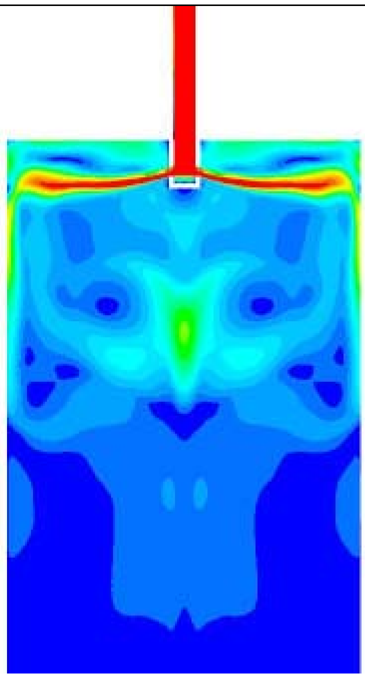
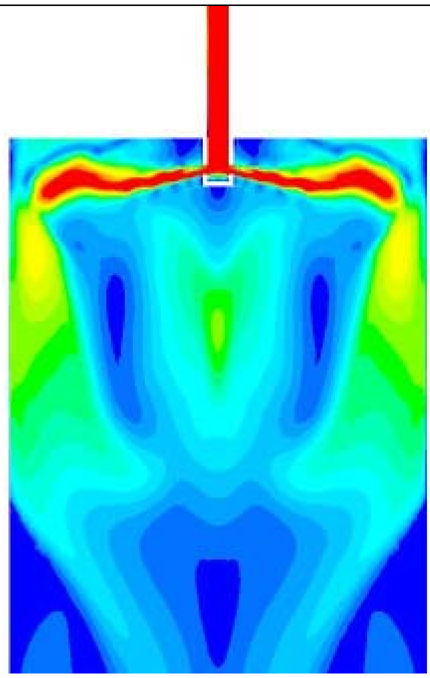
| Experiment designation | Velocity scale [0 – 1 m/s] | **1060mm** width (80mm submergence; 1.3 m/min) | **1250mm** width (80mm submergence; 1.3 m/min) |
|---|---|---|---|
| **1.15**<br>• angle<br>• port height<br>• well depth<br><br>• -2.5°<br>• 30mm<br>• 20.5mm |  |  |  |

Figure N.17: Experiment 1.15 contours of velocity magnitude on centre plane (range 0 – 1 m/s)

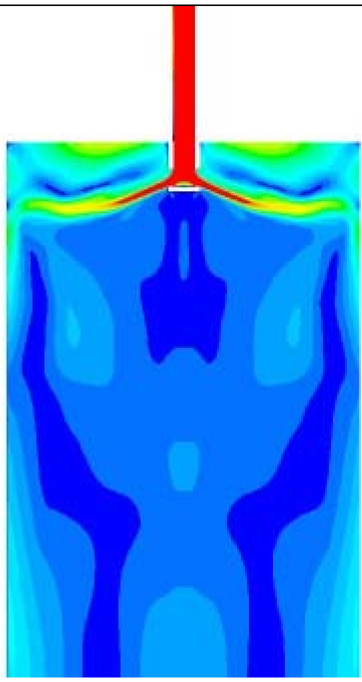
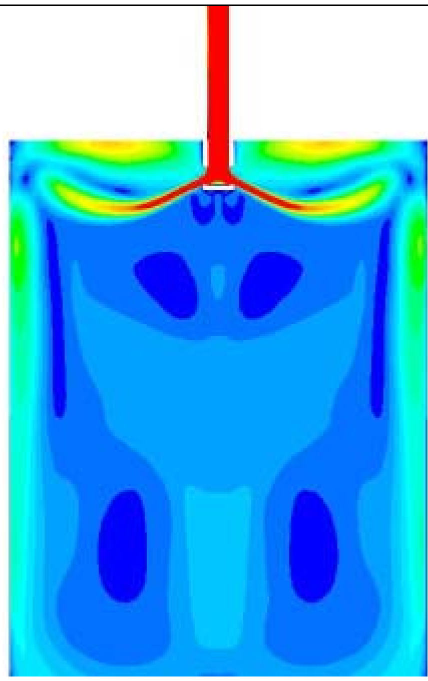
| Experiment designation | Velocity scale [0 – 1 m/s] | 1060mm width (80mm submergence; 1.3 m/min) | 1250mm width (80mm submergence; 1.3 m/min) |
|---|---|---|---|
| **1.16**<br>• angle<br>• port height<br>• well depth<br>• -2.5°<br>• 55mm<br>• 1mm |  |  |  |

Figure N.18: Experiment 1.16 contours of velocity magnitude on centre plane (range 0 – 1 m/s)

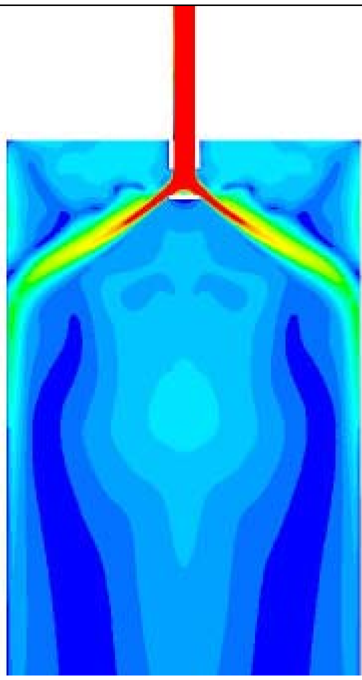
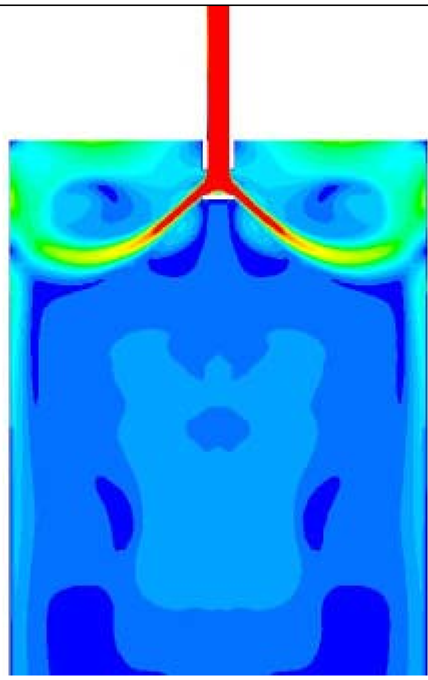
| Experiment designation | Velocity scale [0 – 1 m/s] | 1060mm width (80mm submergence; 1.3 m/min) | 1250mm width (80mm submergence; 1.3 m/min) |
|---|---|---|---|
| **2.0_linear**<br>• angle<br>• port height<br>• well depth<br>• -20°<br>• 80mm<br>• 1mm |  |  |  |

Figure N.19: Experiment 2.0_linear contours of velocity magnitude on centre plane (range 0 – 1 m/s)

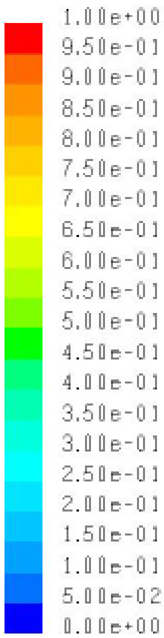
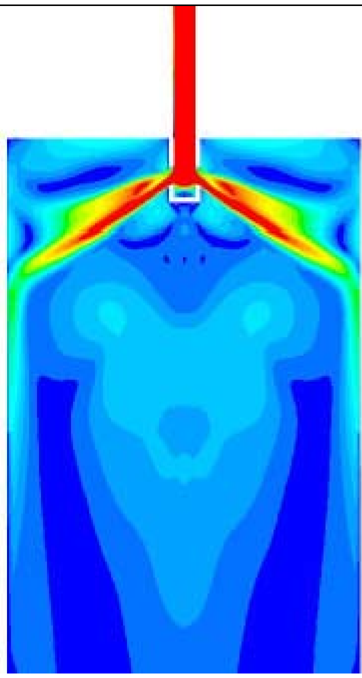
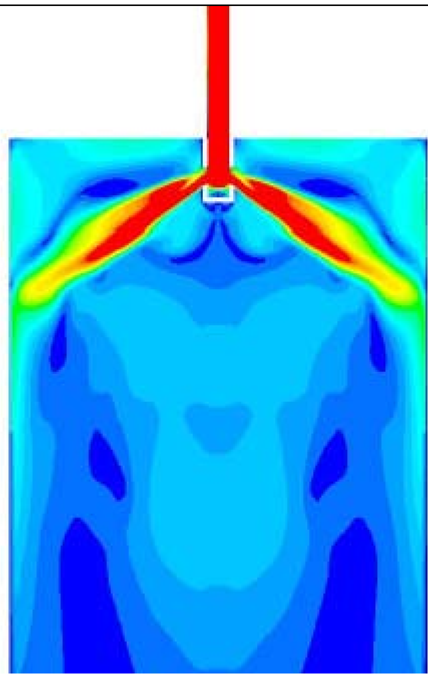
| **Experiment designation** | **Velocity scale [0 – 1 m/s]** | **1060mm width (80mm submergence; 1.3 m/min)** | **1250mm width (80mm submergence; 1.3 m/min)** |
|---|---|---|---|
| **2.0_quadratic**<br>• angle<br>• port height<br>• well depth<br>• -20º<br>• 55.5mm<br>• 40mm |  |  |  |

Figure N.20: Experiment 2.0_quadratic contours of velocity magnitude on centre plane (range 0 – 1 m/s)