APPENDIX O

O. Summary: CFD results of best 4 SEN designs of 3D design exploration

O.1 Summary of Results

The four best designs (lowest multi-objective values) to further explore are:

- 1.0
- 1.7
- 2.0_linear
- 2.0_quadratic

The flow fields in each of these cases (for both widths of 1060 and 1250mm) are shown in section O.2, using the following contours of magnitude, as well as 3D path lines:

- contours of velocity on the symmetry plane
- contours of helicity[1] on the symmetry plane
- contours of turbulent kinetic energy on symmetry plane
- contours of vorticity on the symmetry plane
- contours of shear stress on the wide mould walls
- contours of temperature on the symmetry plane
- path lines originating from the SEN inlet, coloured by vorticity magnitude

These views were generated using FLUENT's post-processing capabilities.

[1] Helicity was defined in Chapter 4, footnote 14 [10].

O.2 CFD Results: contours of magnitude on symmetry plane (last iterations) and path lines

O.2.1 Experiment 1.0

Figures O.1 – O.7

O.2.2 Experiment 1.7

Figures O.8 – O.14

O.2.3 Experiment 2.0_linear

Figures O.15 – O.21

O.2.4 Experiment 2.0_quadratic

Figures O.22 – O.28

O.2.1 Experiment: 1.0

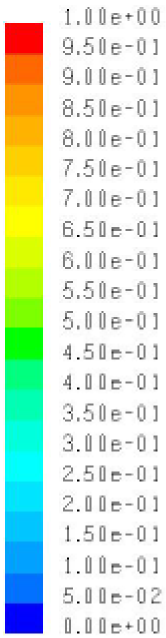
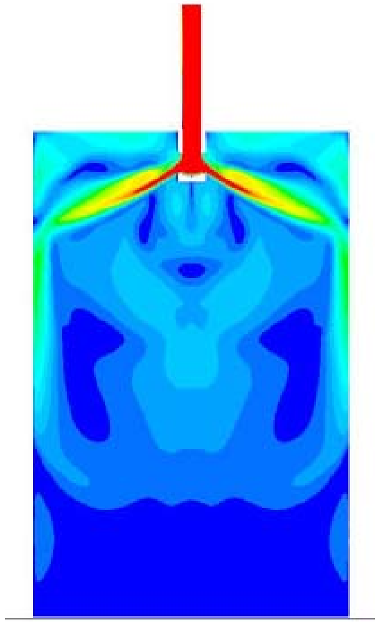
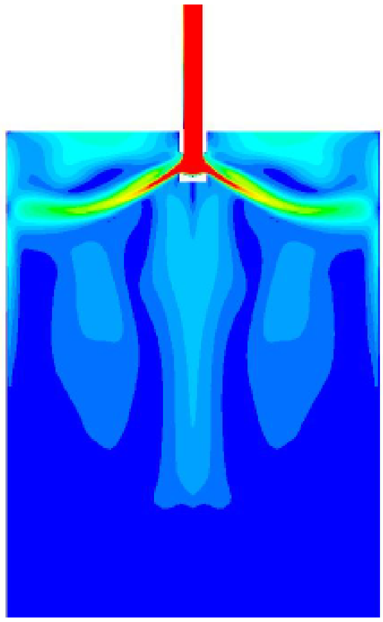
Experiment designation	**Velocity scale [0 – 1 m/s]**	**1060mm width (80mm submergence; 1.3 m/min)**	**1250mm width (80mm submergence; 1.3 m/min)**
1.0 • angle • port height • well depth • 15° (up) • 70mm • 0mm			

Figure O.1: Contours of velocity magnitude on the symmetry plane (range 0 – 1 m/s)

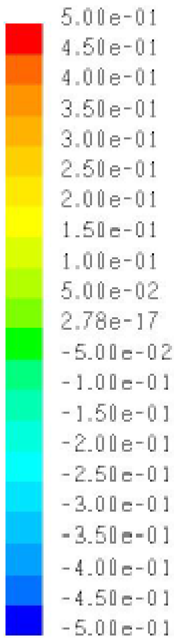
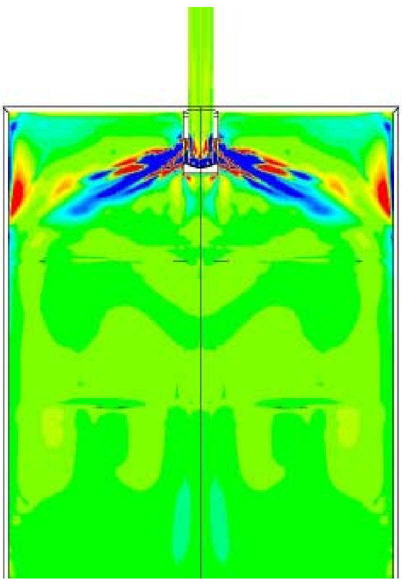
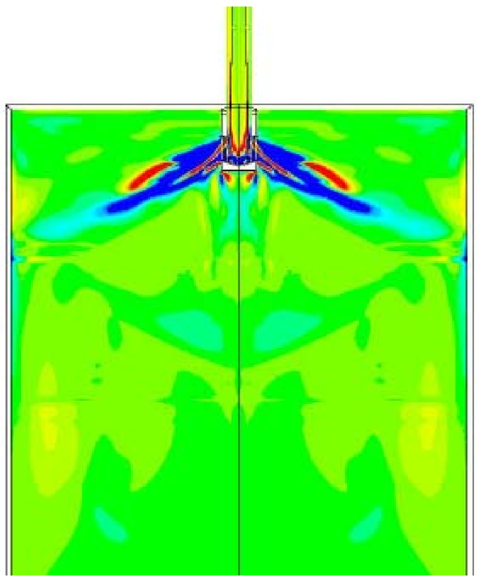
Experiment designation	**Helicity scale [-0.5 – 0.5 m/s^2]**	**1060mm width (80mm submergence; 1.3 m/min)**	**1250mm width (80mm submergence; 1.3 m/min)**
1.0 • angle • port height • well depth • 15° (up) • 70mm • 0mm			

Figure O.2: Contours of helicity on the symmetry plane (range –0.5 – 0.5 m/s^2)

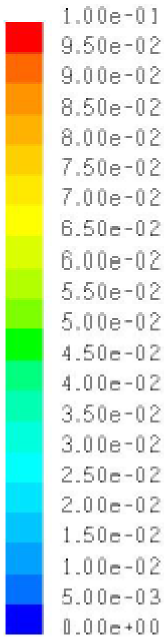
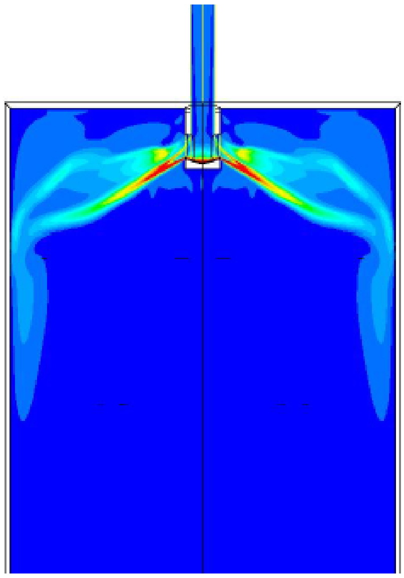
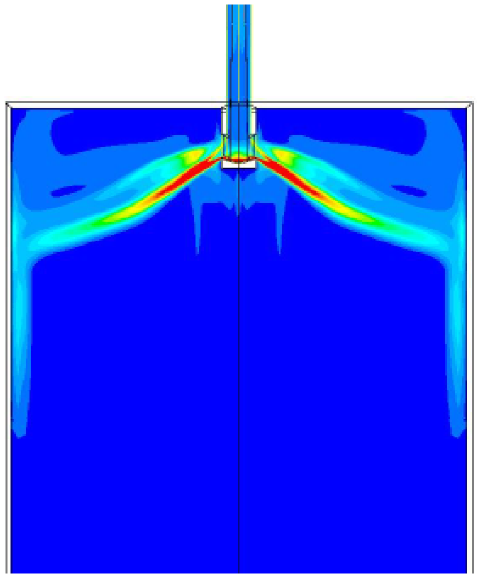
Experiment designation	**TKE scale** **[0 – 0.1 m^2/s^2]**	**1060mm width** **(80mm submergence; 1.3 m/min)**	**1250mm width** **(80mm submergence; 1.3 m/min)**
1.0 • angle • port height • well depth • 15° (up) • 70mm • 0mm			

Figure O.3: Contours of turbulent kinetic energy on symmetry plane (range 0 – 0.1 m^2/s^2)

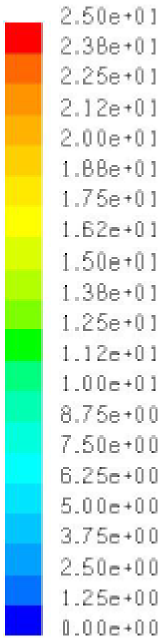
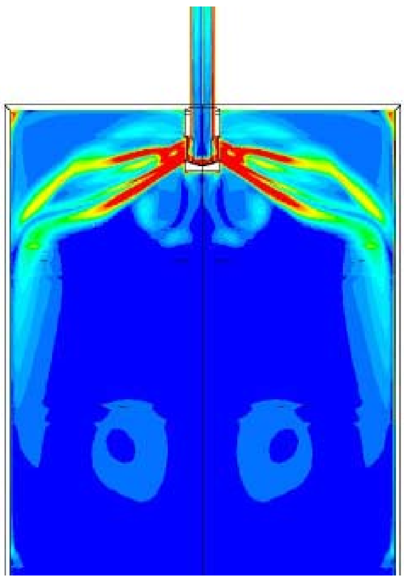
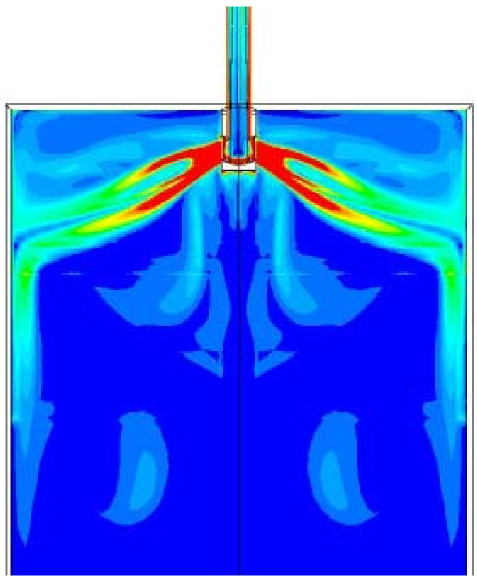
Experiment designation	**Vorticity scale** **[0 – 25 s^{-1}]**	**1060mm width** **(80mm submergence; 1.3 m/min)**	**1250mm width** **(80mm submergence; 1.3 m/min)**
1.0 • angle • port height • well depth • 15° (up) • 70mm • 0mm			

Figure O.4: Contours of vorticity on the symmetry plane (range 0 – 25 s^{-1})

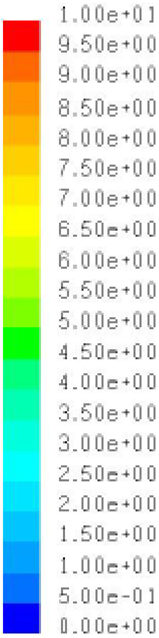
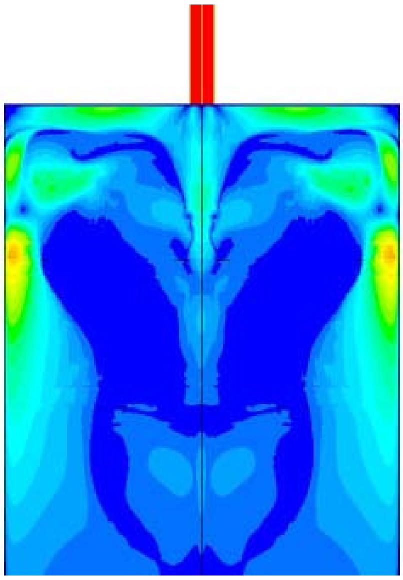
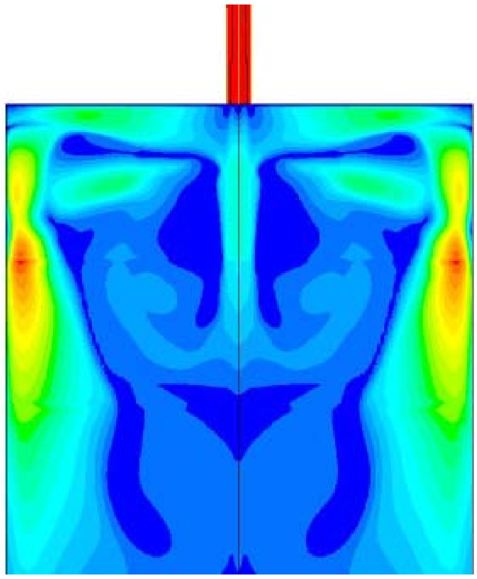
Experiment designation	**Shear stress scale [0 – 10 Pa]**	**1060mm width (80mm submergence; 1.3 m/min)**	**1250mm width (80mm submergence; 1.3 m/min)**
1.0 • angle • port height • well depth • 15º (up) • 70mm • 0mm	 		

Figure O.5: Contours of shear stress on the wide mould walls (range 0 – 10 Pa)

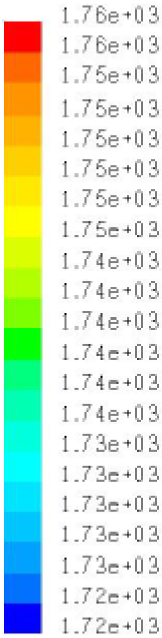
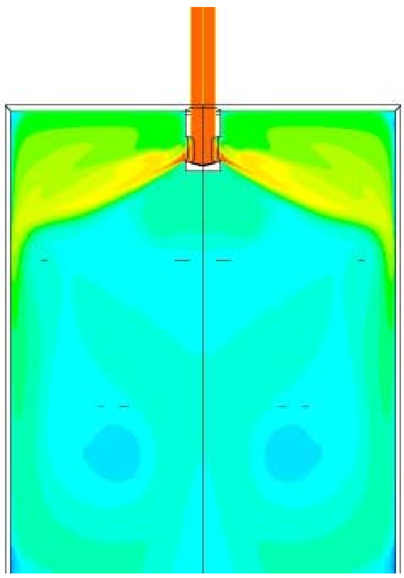
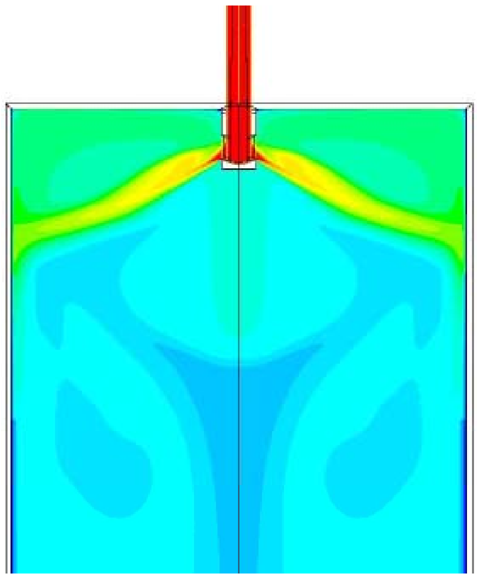
Experiment designation	**Temp. scale [1723 – 1758 K]**	**1060mm width (80mm submergence; 1.3 m/min)**	**1250mm width (80mm submergence; 1.3 m/min)**
1.0 • angle • port height • well depth • 15º (up) • 70mm • 0mm	 		

Figure O.6: Contours of temperature on the symmetry plane (range 1723 – 1758 K)

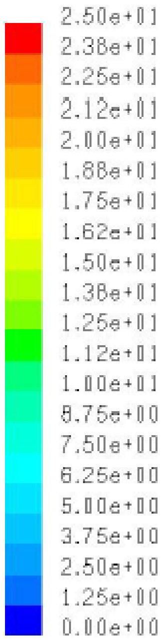
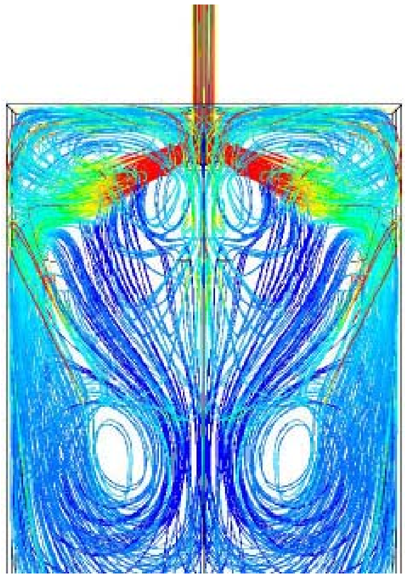
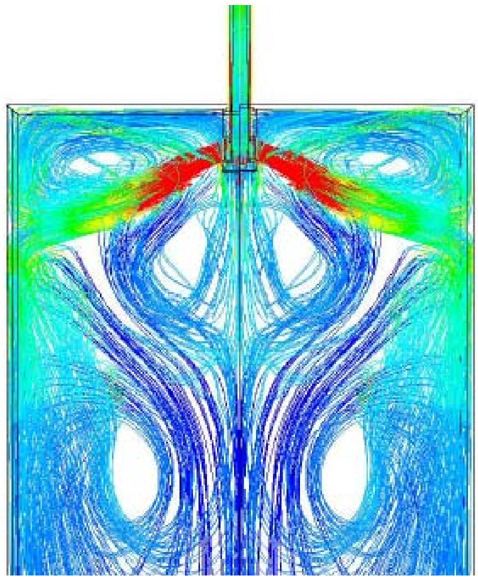
Experiment designation	**Vorticity scale [0 – 25 s^{-1}]**	**1060mm width (80mm submergence; 1.3 m/min)**	**1250mm width (80mm submergence; 1.3 m/min)**
1.0 • angle • port height • well depth • 15º (up) • 70mm • 0mm			

Figure O.7: Path lines originating from the SEN inlet, coloured by vorticity magnitude (range of vorticity 0 – 25 s^{-1})

O.2.2 Experiment: 1.7

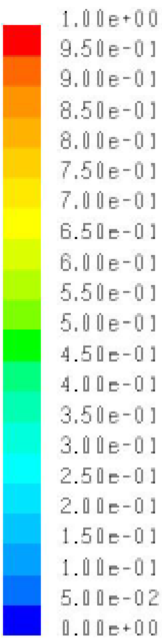
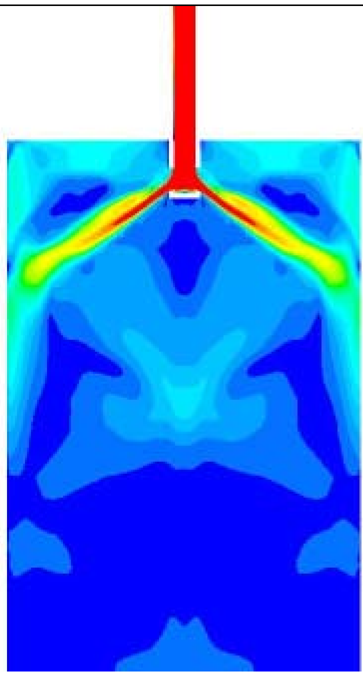
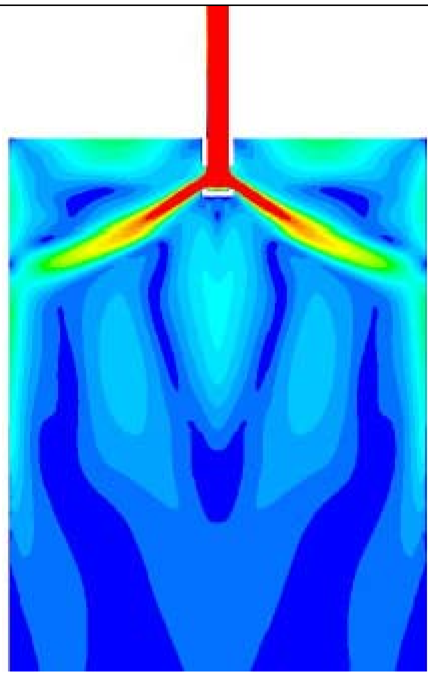
Experiment designation	**Velocity scale [0 – 1 m/s]**	**1060mm width (80mm submergence; 1.3 m/min)**	**1250mm width (80mm submergence; 1.3 m/min)**
1.7 • angle • port height • well depth • -12.9º • 69.9mm • 8.9mm			

Figure O.8: Contours of velocity magnitude on the symmetry plane (range 0 – 1 m/s)

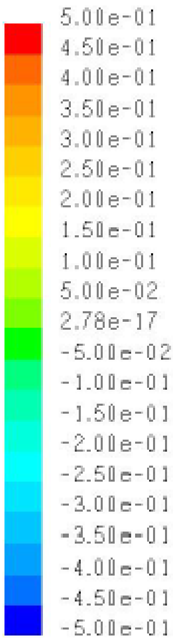
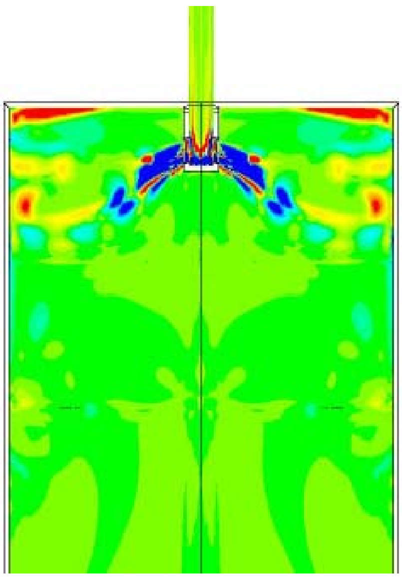
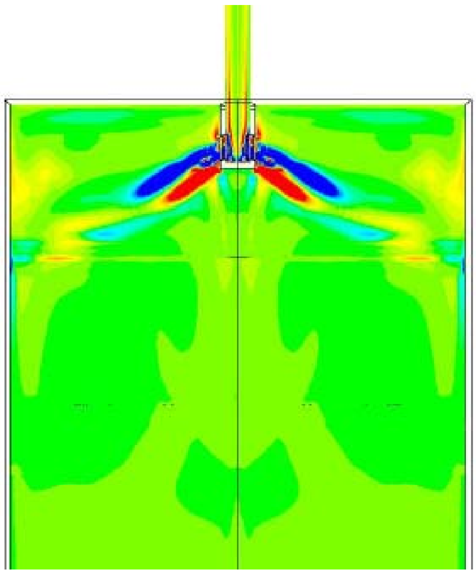
Experiment designation	**Helicity scale [-0.5 – 0.5 m/s^2]**	**1060mm width (80mm submergence; 1.3 m/min)**	**1250mm width (80mm submergence; 1.3 m/min)**
1.7 • angle • port height • well depth • -12.9º • 69.9mm • 8.9mm			

Figure O.9: Contours of helicity on the symmetry plane (range –0.5 – 0.5 m/s^2)

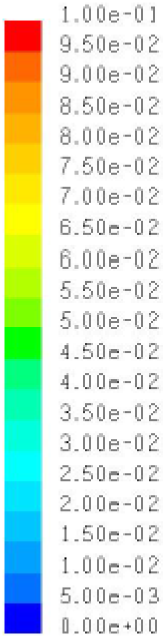
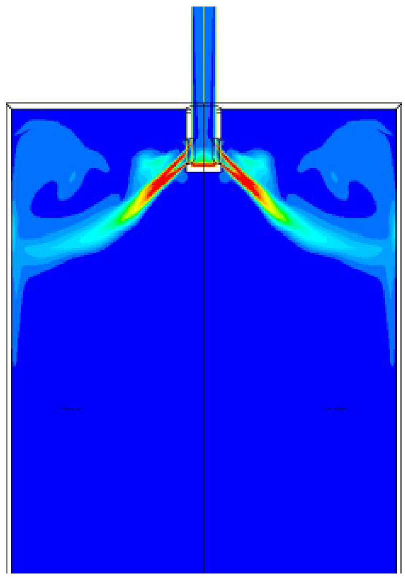
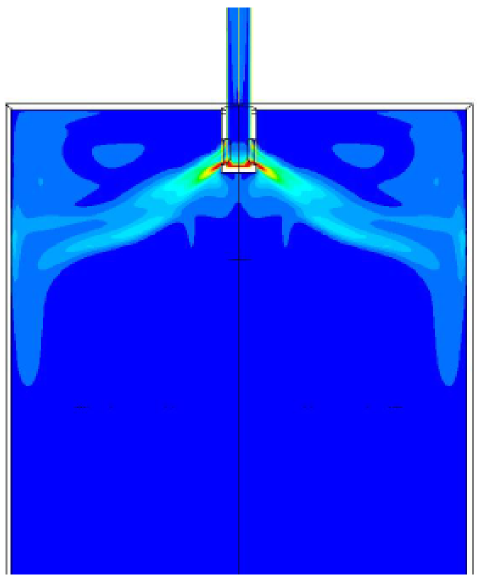
Experiment designation	TKE scale [0 – 0.1 m²/s²]	1060mm width (80mm submergence; 1.3 m/min)	1250mm width (80mm submergence; 1.3 m/min)
1.7 • angle • port height • well depth • -12.9º • 69.9mm • 8.9mm			

Figure O.10: Contours of turbulent kinetic energy on symmetry plane (range 0 – 0.1 m²/s²)

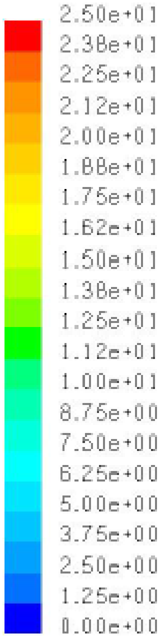
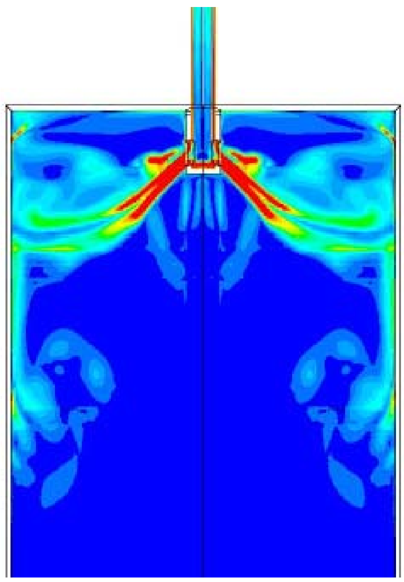
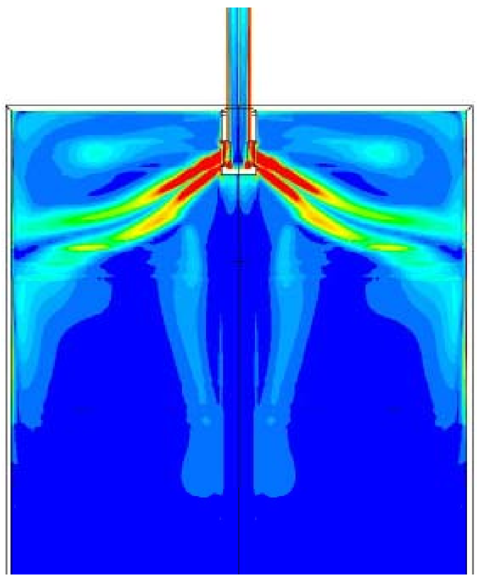
Experiment designation	Vorticity scale [0 – 25 s⁻¹]	1060mm width (80mm submergence; 1.3 m/min)	1250mm width (80mm submergence; 1.3 m/min)
1.7 • angle • port height • well depth • -12.9º • 69.9mm • 8.9mm			

Figure O.11: Contours of vorticity on the symmetry plane (range 0 – 25 s⁻¹)

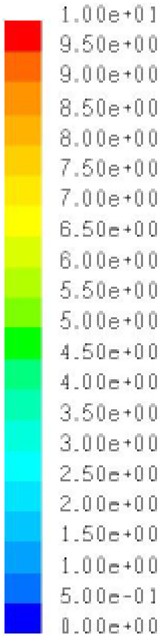
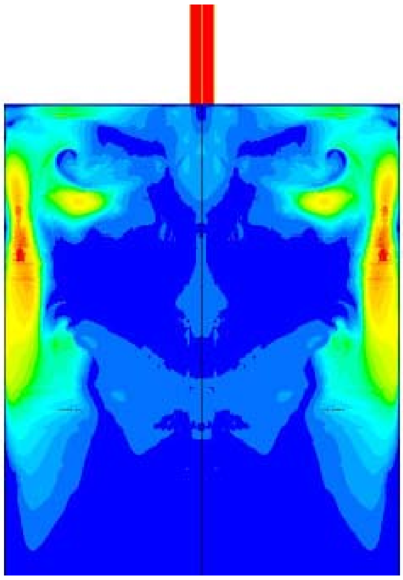
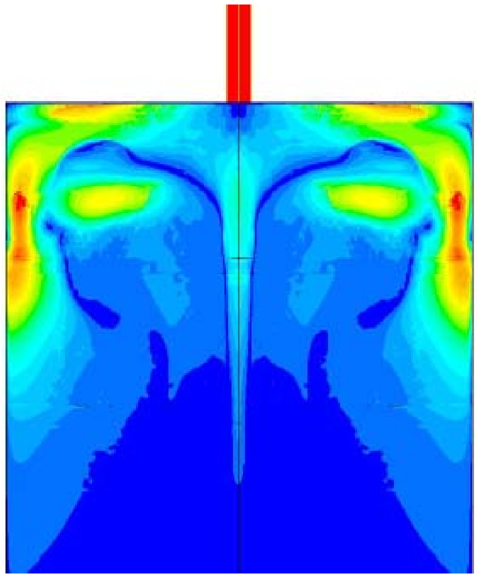
Experiment designation	Shear stress scale [0 – 10 Pa]	**1060mm** width (80mm submergence; 1.3 m/min)	**1250mm** width (80mm submergence; 1.3 m/min)
1.7 • angle • port height • well depth • -12.9° • 69.9mm • 8.9mm			

Figure O.12: Contours of shear stress on the wide mould walls (range 0 – 10 Pa)

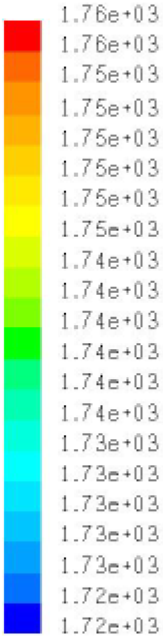
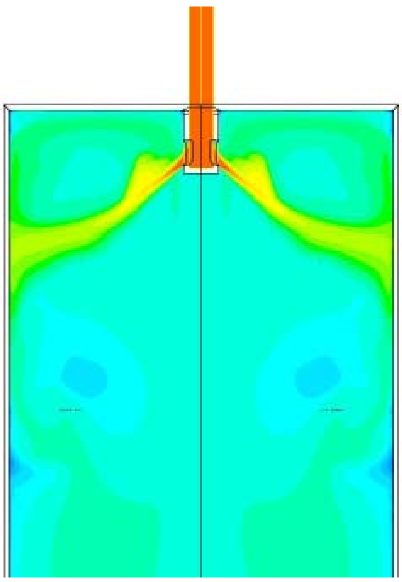
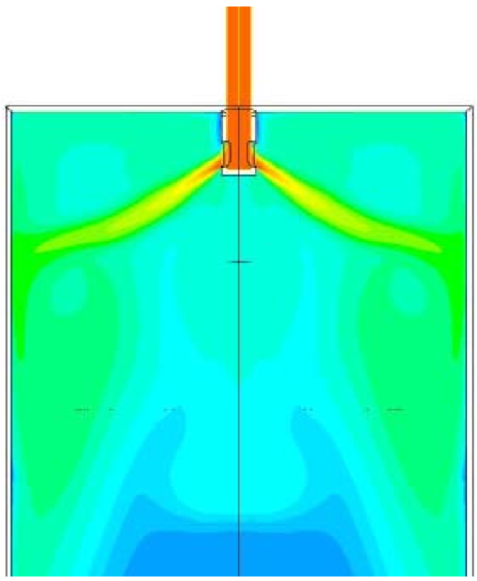
Experiment designation	Temp. scale [1723 – 1758 K]	**1060mm** width (80mm submergence; 1.3 m/min)	**1250mm** width (80mm submergence; 1.3 m/min)
1.7 • angle • port height • well depth • -12.9° • 69.9mm • 8.9mm			

Figure O.13: Contours of temperature on the symmetry plane (range 1723 – 1758 K)

<table>
<tr><th>Experiment designation</th><th>Vorticity scale [0 – 25 s^{-1}]</th><th>1060mm width
(80mm submergence; 1.3 m/min)</th><th>1250mm width
(80mm submergence; 1.3 m/min)</th></tr>
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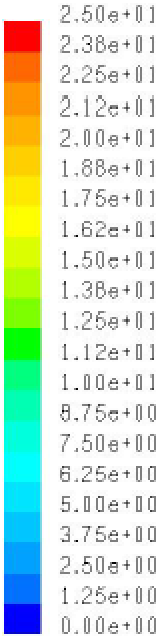
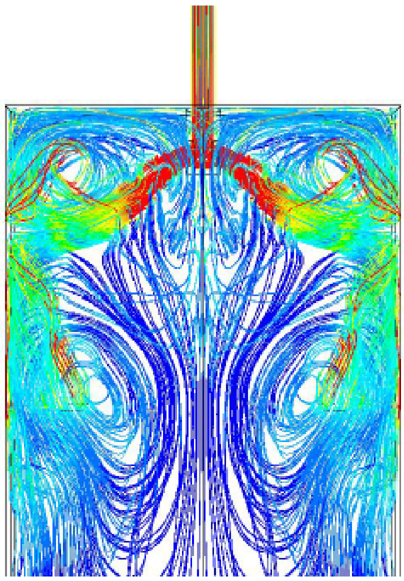
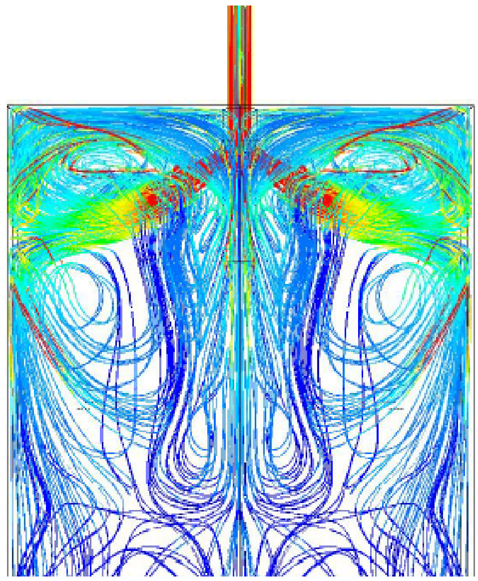
• angle
• port height
• well depth
• -12.9º
• 69.9mm
• 8.9mm</td><td>
</td><td></td><td></td></tr>
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Figure O.14: Path lines originating from the SEN inlet, coloured by vorticity magnitude (range of vorticity 0 – 25 s^{-1})

O.2.3 Experiment: 2.0_linear

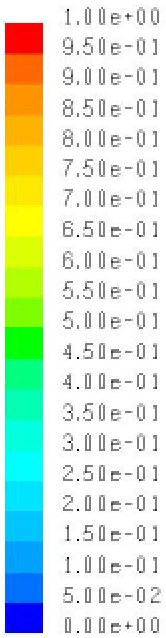
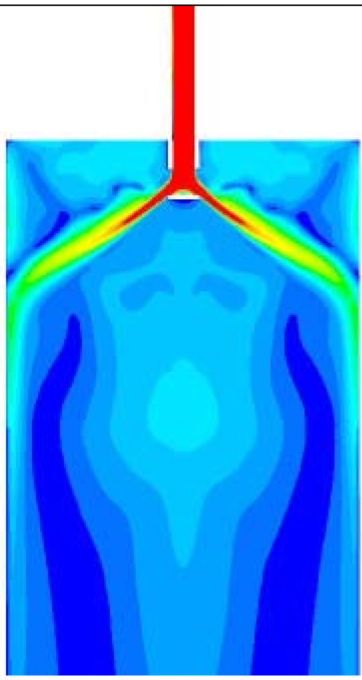
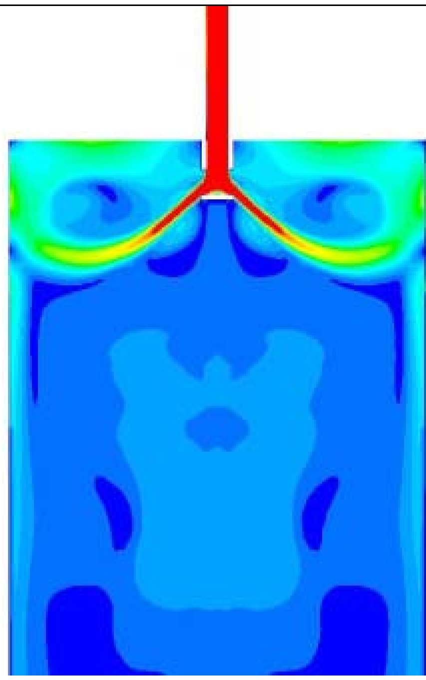
Experiment designation	Velocity scale [0 – 1 m/s]	**1060mm width** (80mm submergence; 1.3 m/min)	**1250mm width** (80mm submergence; 1.3 m/min)
2.0_linear • angle • port height • well depth • -20º • 80mm • 1mm			

Figure O.15: Contours of velocity magnitude on the symmetry plane (range 0 – 1 m/s)

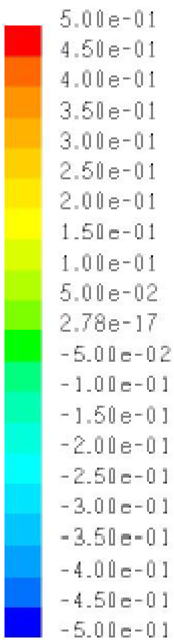
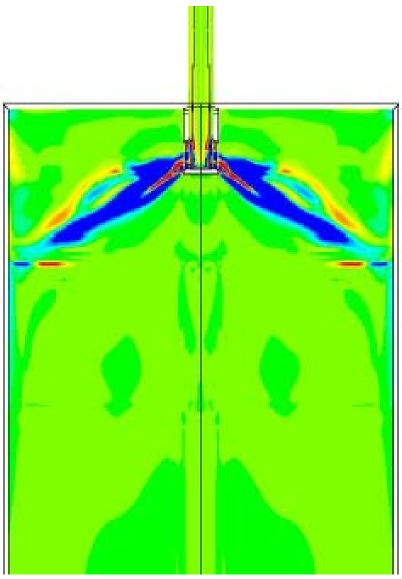
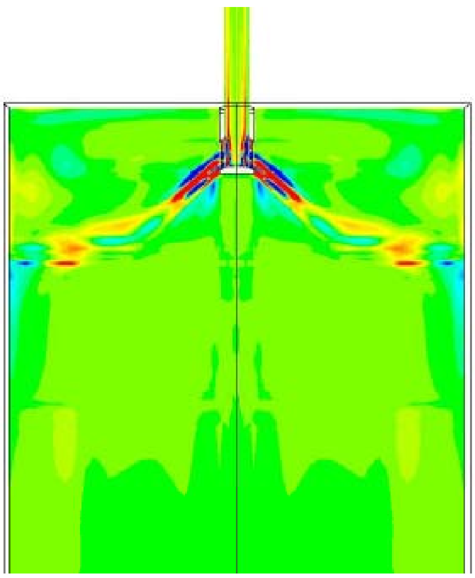
Experiment designation	Helicity scale [-0.5 – 0.5 m/s^2]	**1060mm width** (80mm submergence; 1.3 m/min)	**1250mm width** (80mm submergence; 1.3 m/min)
2.0_linear • angle • port height • well depth • -20º • 80mm • 1mm			

Figure O.16: Contours of helicity on the symmetry plane (range –0.5 – 0.5 m/s^2)

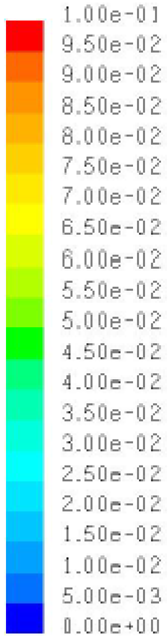
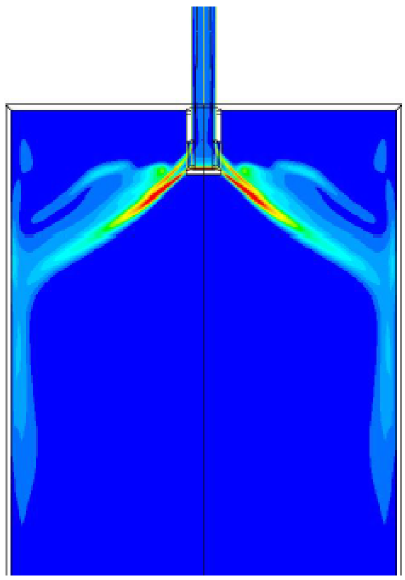
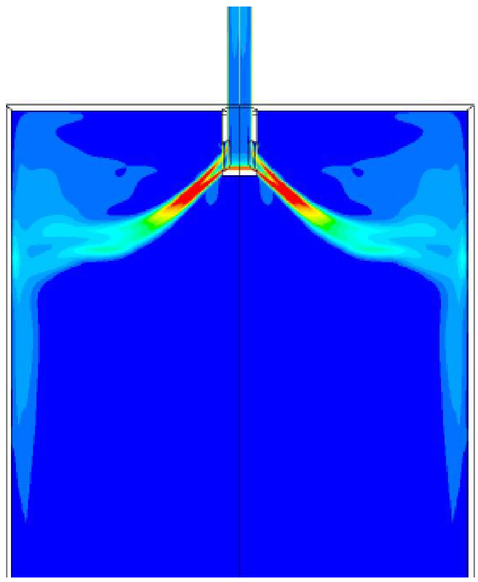
Experiment designation	**TKE scale [0 – 0.1 m^2/s^2]**	**1060mm width (80mm submergence; 1.3 m/min)**	**1250mm width (80mm submergence; 1.3 m/min)**
2.0_linear • angle • port height • well depth • -20º • 80mm • 1mm			

Figure O.17: Contours of turbulent kinetic energy on symmetry plane (range 0 – 0.1 m^2/s^2)

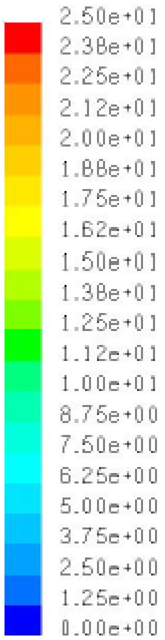
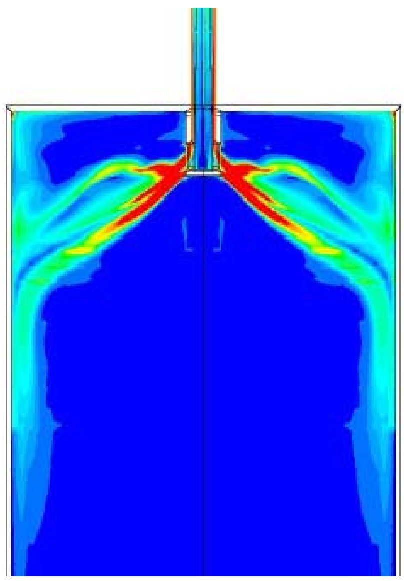
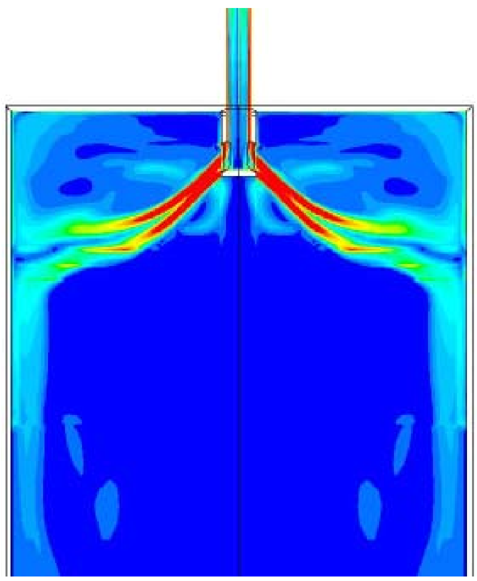
Experiment designation	**Vorticity scale [0 – 25 s^{-1}]**	**1060mm width (80mm submergence; 1.3 m/min)**	**1250mm width (80mm submergence; 1.3 m/min)**
2.0_linear • angle • port height • well depth • -20º • 80mm • 1mm			

Figure O.18: Contours of vorticity on the symmetry plane (range 0 – 25 s^{-1})

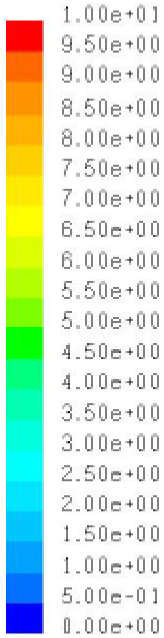
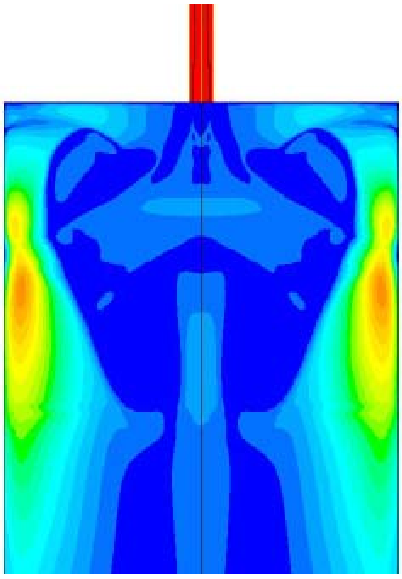
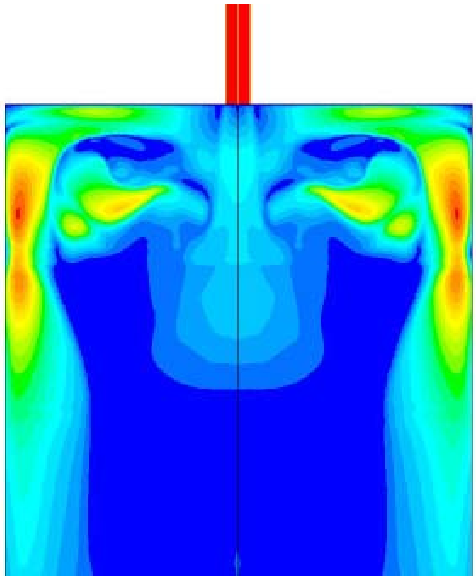
Experiment designation	**Shear stress scale [0 – 10 Pa]**	**1060mm width (80mm submergence; 1.3 m/min)**	**1250mm width (80mm submergence; 1.3 m/min)**
2.0_linear • angle • port height • well depth • -20º • 80mm • 1mm			

Figure O.19: Contours of shear stress on the wide mould walls (range 0 – 10 Pa)

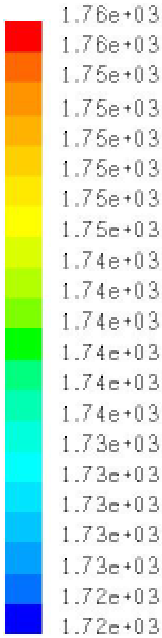
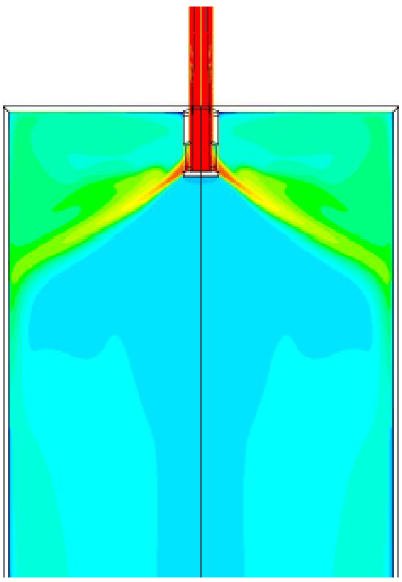
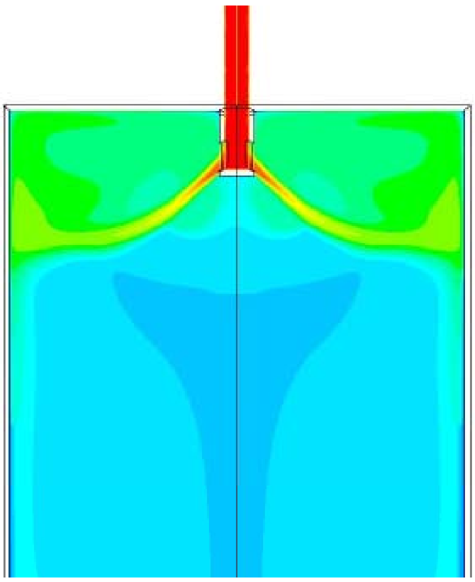
Experiment designation	**Temp. scale [1723 – 1758 K]**	**1060mm width (80mm submergence; 1.3 m/min)**	**1250mm width (80mm submergence; 1.3 m/min)**
2.0_linear • angle • port height • well depth • -20º • 80mm • 1mm			

Figure O.20: Contours of temperature on the symmetry plane (range 1723 – 1758 K)

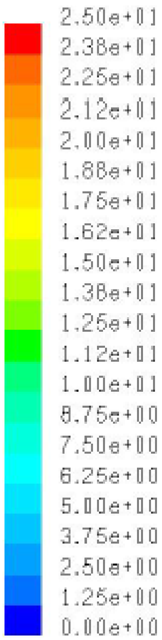
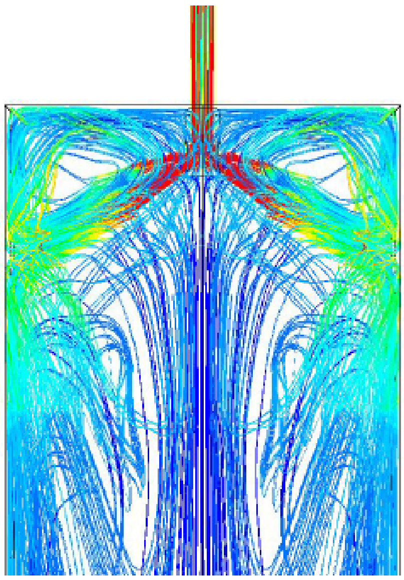
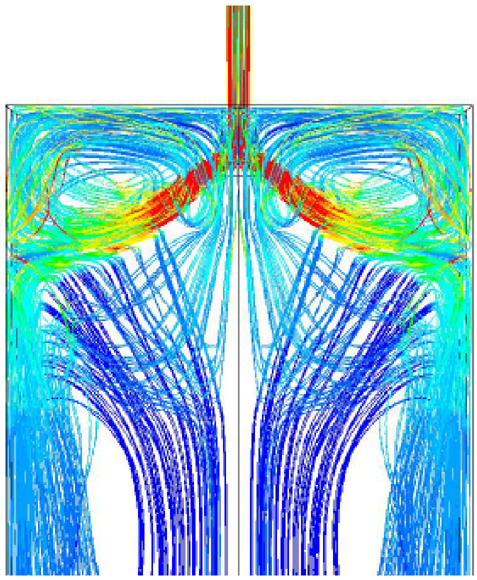
Experiment designation	**Vorticity scale [0 – 25 s^{-1}]**	**1060mm width** (80mm submergence; 1.3 m/min)	**1250mm width** (80mm submergence; 1.3 m/min)
2.0_linear • angle • port height • well depth • -20º • 80mm • 1mm			

Figure O.21: Path lines originating from the SEN inlet, coloured by vorticity magnitude (range of vorticity 0 – 25 s^{-1})

O.2.4 Experiment: 2.0_quadratic

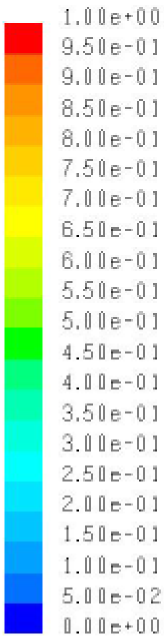
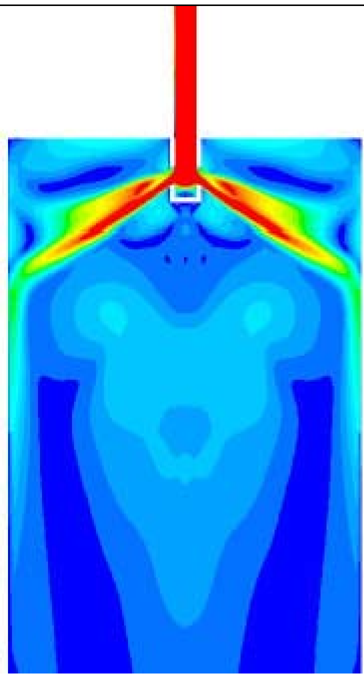
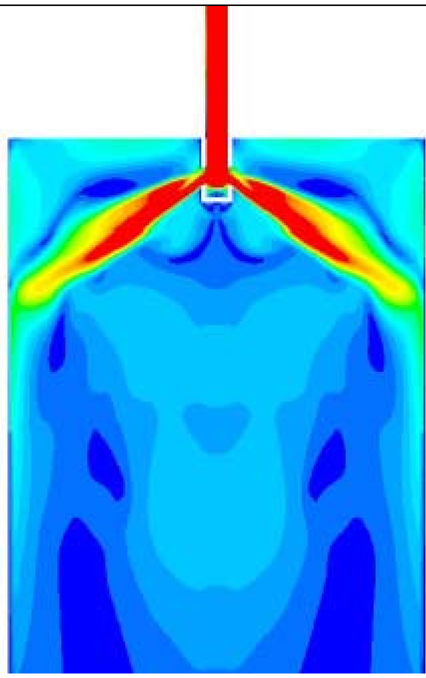
Experiment designation	Velocity scale [0 – 1 m/s]	**1060mm width** (80mm submergence; 1.3 m/min)	**1250mm width** (80mm submergence; 1.3 m/min)
2.0_quadratic • angle • port height • well depth • -20º • 55.5mm • 40mm			

Figure O.22: Contours of velocity magnitude on the symmetry plane (range 0 – 1 m/s)

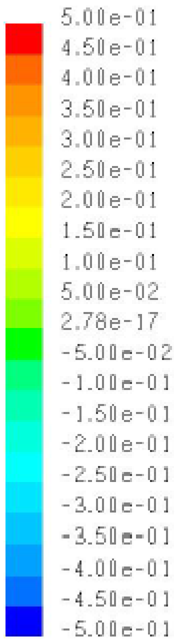
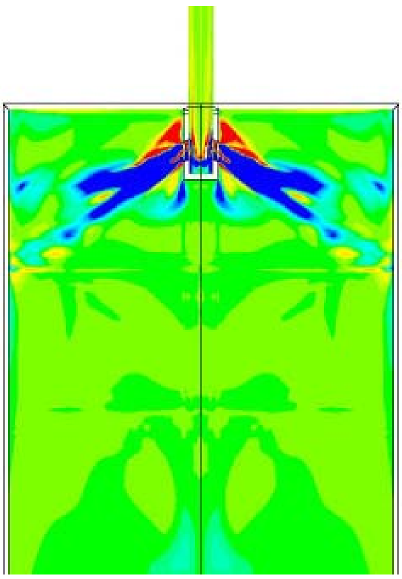
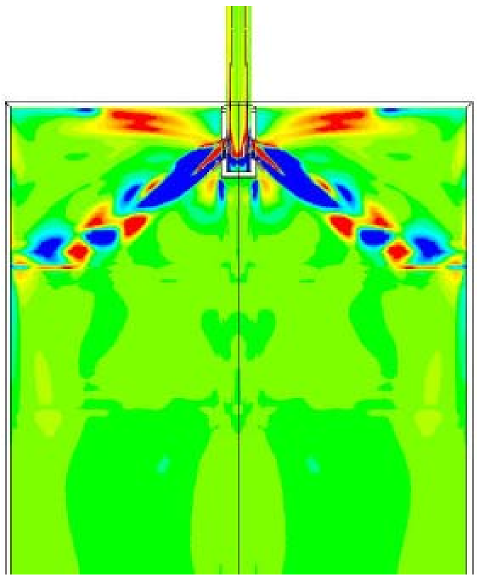
Experiment designation	Helicity scale [-0.5 – 0.5 m/s^2]	**1060mm width** (80mm submergence; 1.3 m/min)	**1250mm width** (80mm submergence; 1.3 m/min)
2.0_quadratic • angle • port height • well depth • -20º • 55.5mm • 40mm			

Figure O.23: Contours of helicity on the symmetry plane (range –0.5 – 0.5 m/s^2)

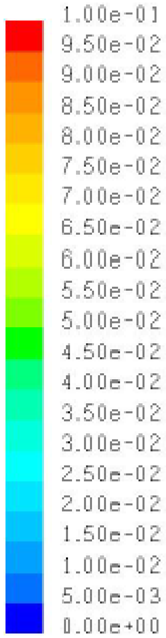
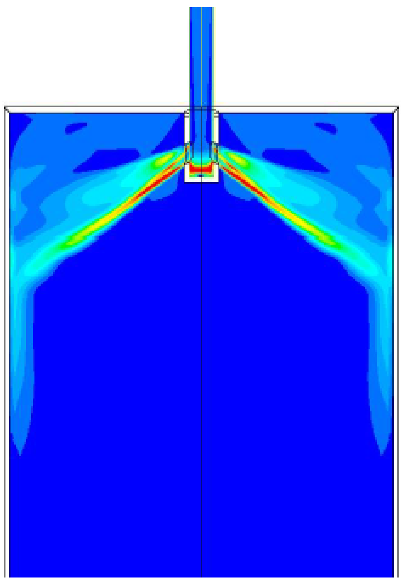
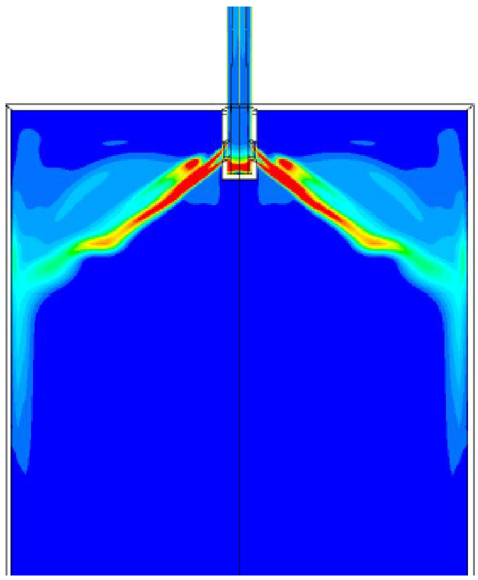
Experiment designation	**TKE scale [0 – 0.1 m^2/s^2]**	**1060mm width (80mm submergence; 1.3 m/min)**	**1250mm width (80mm submergence; 1.3 m/min)**
2.0_quadratic • angle • port height • well depth • -20º • 55.5mm • 40mm			

Figure O.24: Contours of turbulent kinetic energy on symmetry plane (range 0 – 0.1 m^2/s^2)

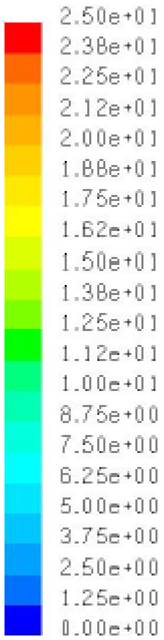
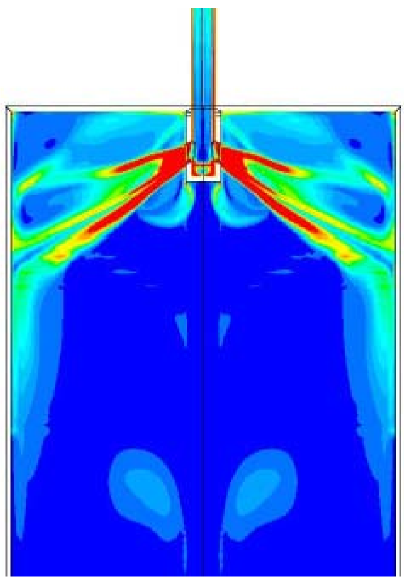
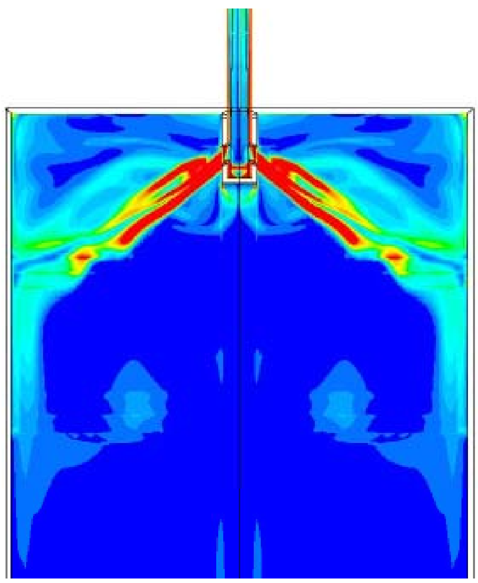
Experiment designation	**Vorticity scale [0 – 25 s^{-1}]**	**1060mm width (80mm submergence; 1.3 m/min)**	**1250mm width (80mm submergence; 1.3 m/min)**
2.0_quadratic • angle • port height • well depth • -20º • 55.5mm • 40mm			

Figure O.25: Contours of vorticity on the symmetry plane (range 0 – 25 s^{-1})

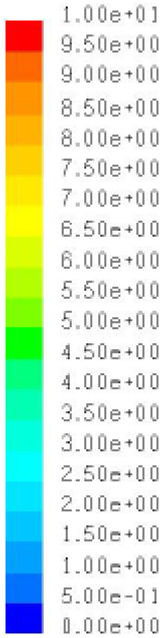
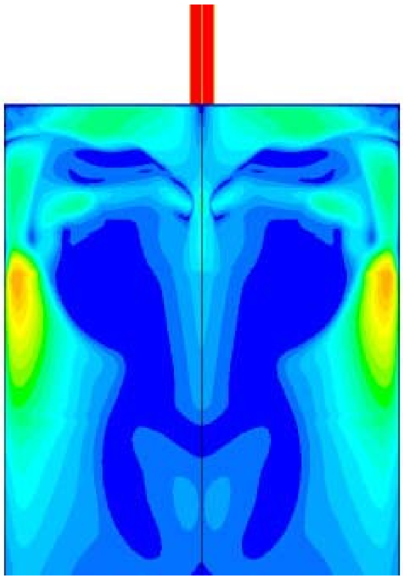
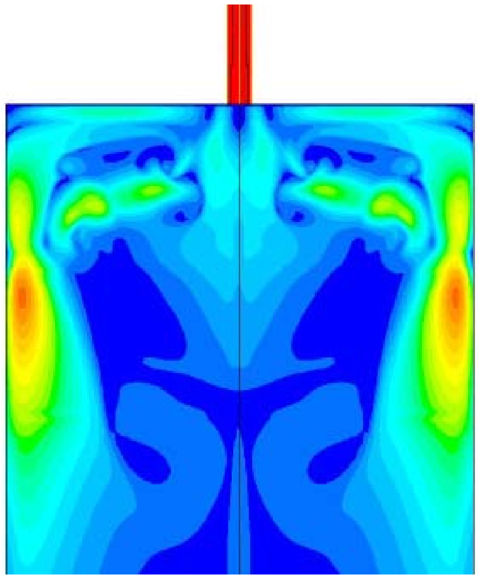
Experiment designation	**Shear stress scale [0 – 10 Pa]**	**1060mm width (80mm submergence; 1.3 m/min)**	**1250mm width (80mm submergence; 1.3 m/min)**
2.0_quadratic • angle • port height • well depth • -20º • 55.5mm • 40mm			

Figure O.26: Contours of shear stress on the wide mould walls (range 0 – 10 Pa)

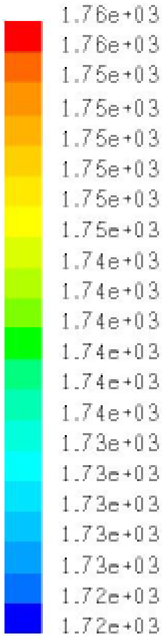
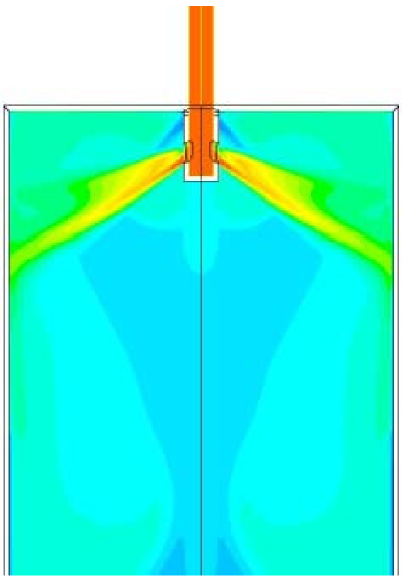
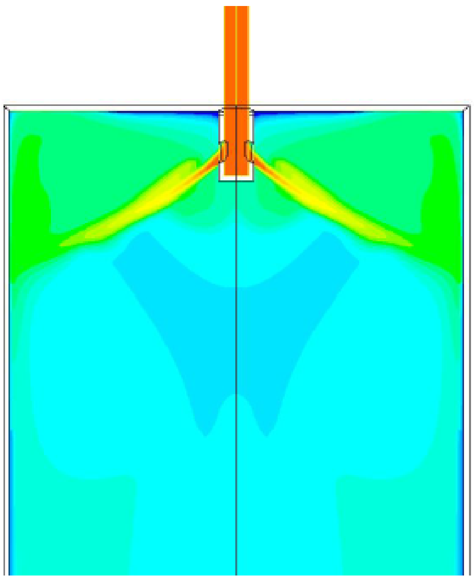
Experiment designation	**TemO. scale [1723 – 1758 K]**	**1060mm width (80mm submergence; 1.3 m/min)**	**1250mm width (80mm submergence; 1.3 m/min)**
2.0_quadratic • angle • port height • well depth • -20º • 55.5mm • 40mm			

Figure O.27: Contours of temperature on the symmetry plane (range 1723 – 1758 K)

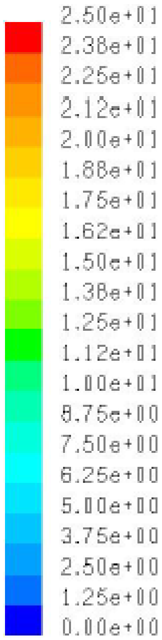
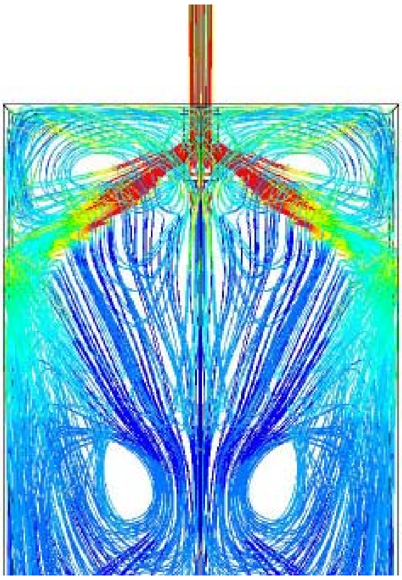
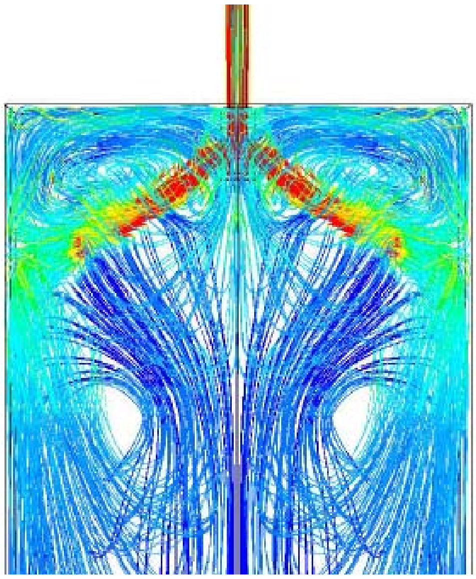
Experiment designation	**Vorticity scale [0 – 25 s^{-1}]**	**1060mm width (80mm submergence; 1.3 m/min)**	**1250mm width (80mm submergence; 1.3 m/min)**
2.0_quadratic • angle • port height • well depth • -20º • 55.5mm • 40mm			

Figure O.28: Path lines originating from the SEN inlet, coloured by vorticity magnitude (range of vorticity 0 – 25 s^{-1})

APPENDIX P

P. CFD results of best 4 SEN designs: iso-surfaces to indicate 3D nature of flow

P.1 General

In order to demonstrate the 3 dimensional nature of the flow field, another display method is used: The jet is displayed in 3D by rendering iso-surfaces[1] of velocity magnitude coloured by turbulent kinetic energy.
The four best designs (lowest multi-objective values) that will be displayed are:

- 1.0
- 1.7
- 2.0_linear
- 2.0_quadratic

The iso-surface of velocity magnitude was in each case chosen to indicate the jet as it emerges from the SEN ports. In Figures P.1 to P.4, one can clearly observe that the jet path varies as the jet moves closer to the wide walls of the mould. Therefore, much of the flow follows an entire different path from the centre plane; consequently, the effect of the walls is quite significant. Thus; meaningful optimisation studies certainly need to take into account the full 3 dimensional flow in typical SEN and mould CFD models.

Refer to section P.2 for the visual depiction of the 3D nature of flow inside the mould cavity.

[1] An iso-surface of velocity magnitude (for example) is when only the surface area where a specified constant velocity magnitude is achieved in the entire flow field is displayed. Of course, other properties may vary over this iso-surface, as turbulent kinetic energy for example.

P.2 CFD Results: Iso-surfaces of velocity magnitude coloured by vorticity (last iterations)

P.2.1 Experiment 1.0

Figure P.1

P.2.2 Experiment 1.7

Figure P.2

P.2.3 Experiment 2.0_linear

Figure P.3

P.2.4 Experiment 2.0_quadratic

Figure P.4

P.2.1 Experiment: 1.0

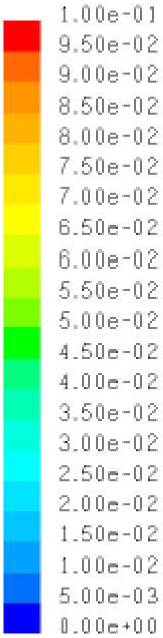
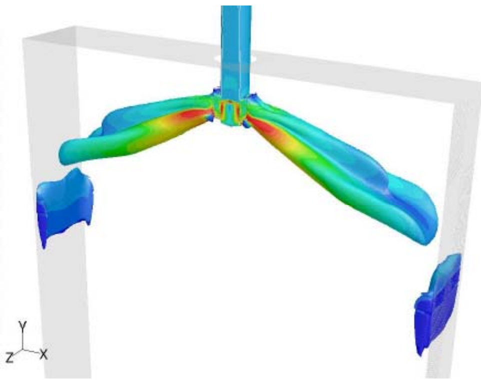
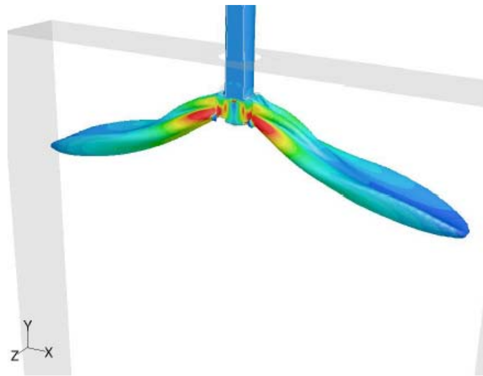
Experiment designation	TKE scale [0 – 0.1 m^2/s^2]	1060mm width (80mm submergence; 1.3 m/min)	1250mm width (80mm submergence; 1.3 m/min)
1.0 • angle • port height • well depth • 15º (up) • 70mm • 0mm			

Figure P.1: Iso-surface of velocity coloured by turbulent kinetic energy (range 0 – 0.1 m^2/s^2)

P.2.2 Experiment: 1.7

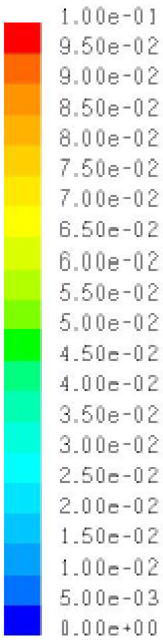
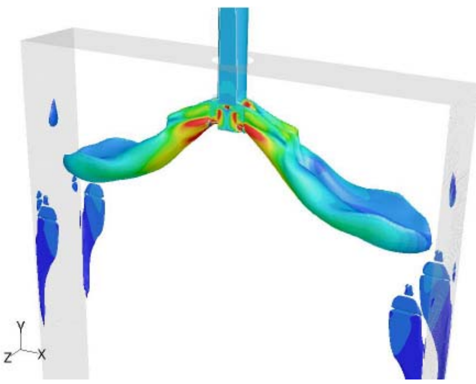
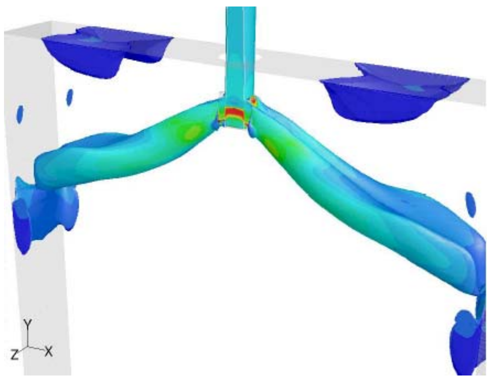
Experiment designation	TKE scale [0 – 0.1 m^2/s^2]	1060mm width (80mm submergence; 1.3 m/min)	1250mm width (80mm submergence; 1.3 m/min)
1.7 • angle • port height • well depth • -12.9º • 69.9mm • 8.9mm			

Figure P.2: Iso-surface of velocity coloured by turbulent kinetic energy (range 0 – 0.1 m^2/s^2)

P.2.3 Experiment: 2.0_linear

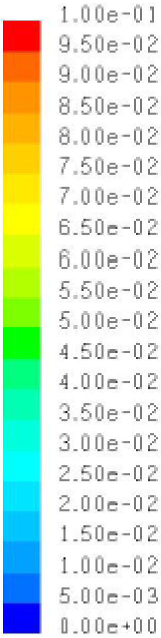
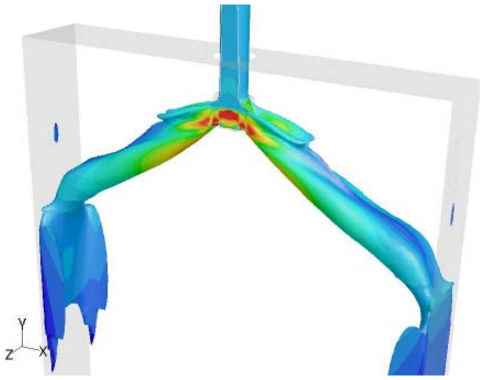
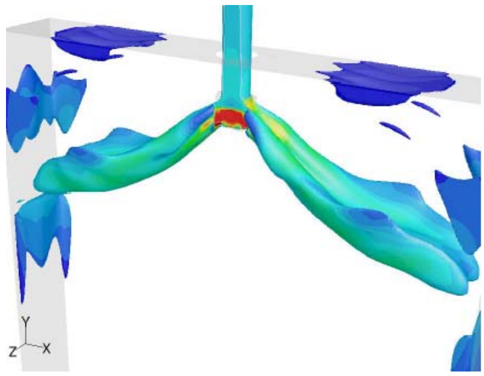
Experiment designation	TKE scale [0 – 0.1 m^2/s^2]	1060mm width (80mm submergence; 1.3 m/min)	1250mm width (80mm submergence; 1.3 m/min)
2.0_linear • angle • port height • well depth • -20º • 80mm • 1mm			

Figure P.3: Iso-surface of velocity coloured by turbulent kinetic energy (range 0 – 0.1 m^2/s^2)

P.2.4 Experiment: 2.0_quadratic

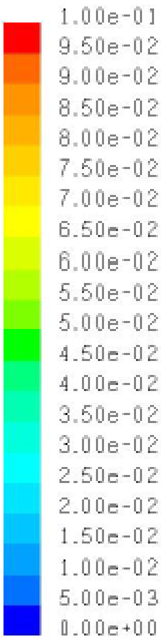
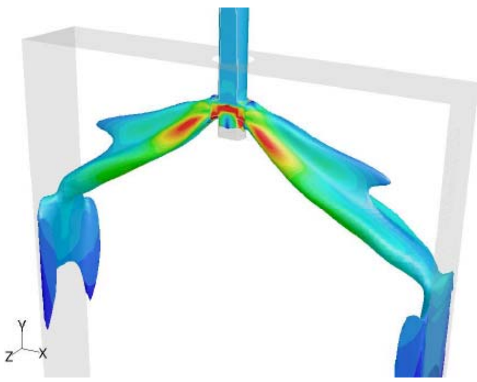
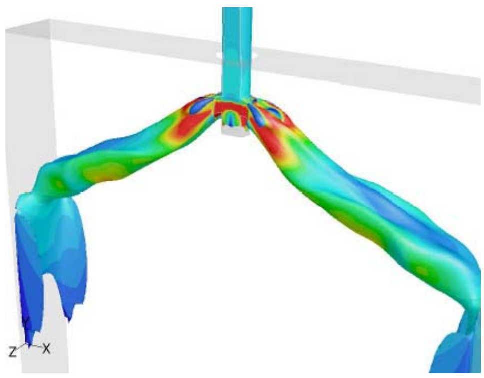
Experiment designation	TKE scale [0 – 0.1 m^2/s^2]	1060mm width (80mm submergence; 1.3 m/min)	1250mm width (80mm submergence; 1.3 m/min)
2.0_quadratic • angle • port height • well depth • -20º • 55.5mm • 40mm			

Figure P.4: Contours of turbulent kinetic energy on symmetry plane (range 0 – 0.1 m^2/s^2)

APPENDIX Q

Q. Validation of optimum SEN design: CFD results compared with water model tests at 80mm and 150mm submergence depth

Q.1 General

The optimum design chosen from the 3D design exploration is the 2.0_linear experiment.

This optimum design is validated at the widest width, namely 1250mm, as the CFD solutions tend to be problematic with increasing width.

The optimum CFD models (full-scale) reflect the real plant circumstances, as liquid steel is used as the fluid. In section Q.2, the 40%-scaled water model results for submergence depths of 80mm and 150mm are compared with the corresponding full-scale CFD models (using contours of velocity and path lines).

The excellent correspondence between the 40%-scaled water model and CFD results (Figures Q.1 to Q.4) simultaneously verifies the assumption that only satisfying Fr-similarity is adequate for typical flow verification.

Q.2 Optimum SEN CFD results validation: 80mm and 150mm submergence

Q.2.1 Submergence depth: 80mm

Figures Q.1 and Q.2

Q.2.2 Submergence depth: 150mm

Figures Q.3 and Q.4

Q.2.1 Submergence depth: 80mm

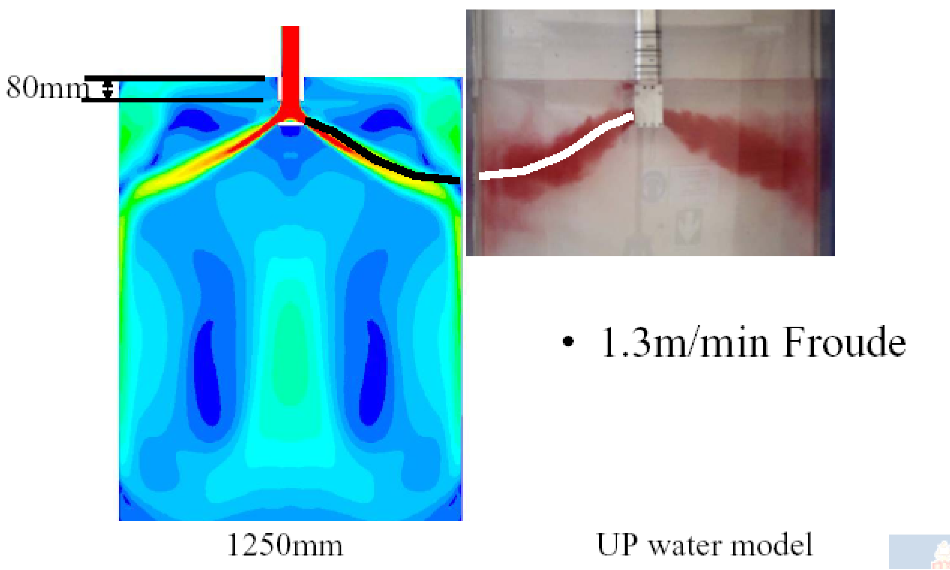
Experiment designation	**Velocity scale [0 – 1 m/s]**	**1250mm width (80mm submergence; 1.3 m/min)**
2.0_linear • angle • port height • well depth • -20º • 80mm • 1mm		

Figure Q.1: Validation of optimum SEN design at 80mm submergence depth, using contours of velocity (scale 0 – 1 m/s)

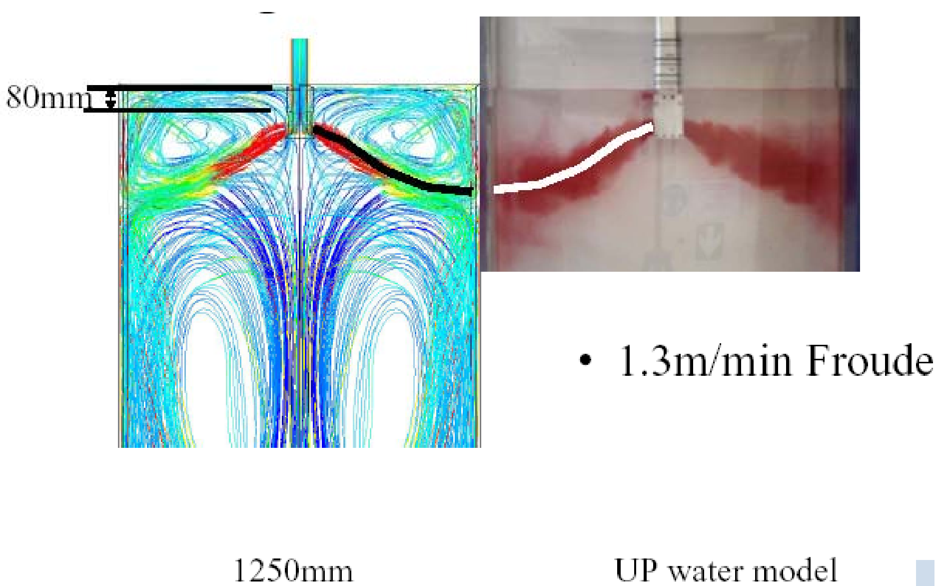
Experiment designation	**Velocity scale [0 – 1 m/s]**	**1250mm width (80mm submergence; 1.3 m/min)**
2.0_linear • angle • port height • well depth • -20º • 80mm • 1mm		

Figure Q.2: Validation of optimum SEN design at 80mm submergence depth, using path lines coloured by velocity magnitude (scale 0 – 1 m/s)

Q.2.2 Submergence depth: 150mm

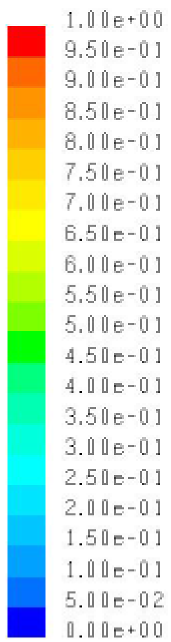
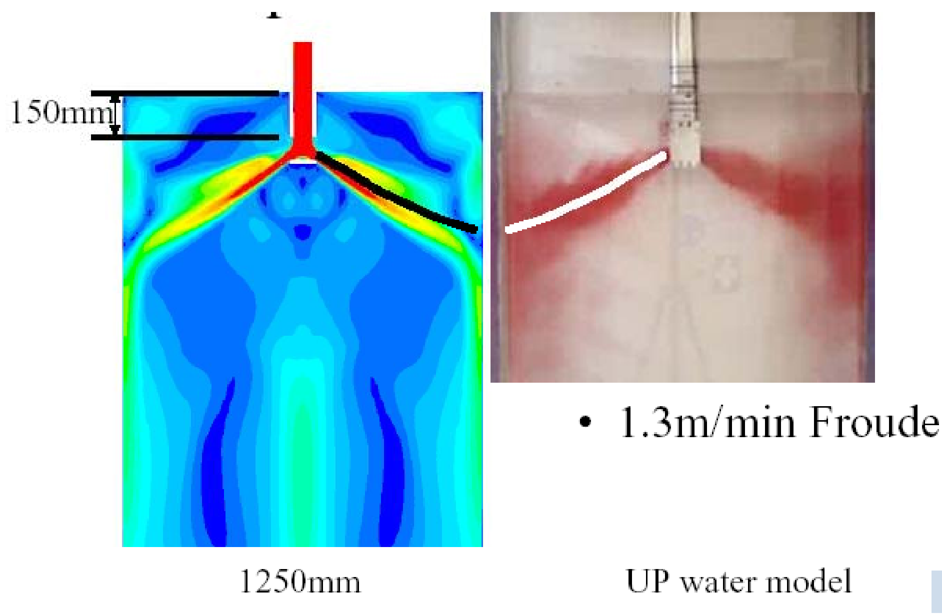
Experiment designation	**Velocity scale [0 – 1 m/s]**	**1250mm width (150mm submergence; 1.3 m/min)**
2.0_linear • angle • port height • well depth • -20º • 80mm • 1mm		

Figure Q.3: Validation of optimum SEN design at 150mm submergence depth, using contours of velocity (scale 0 – 1 m/s)

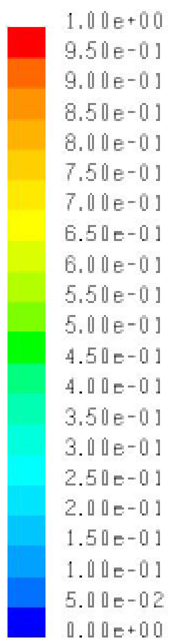
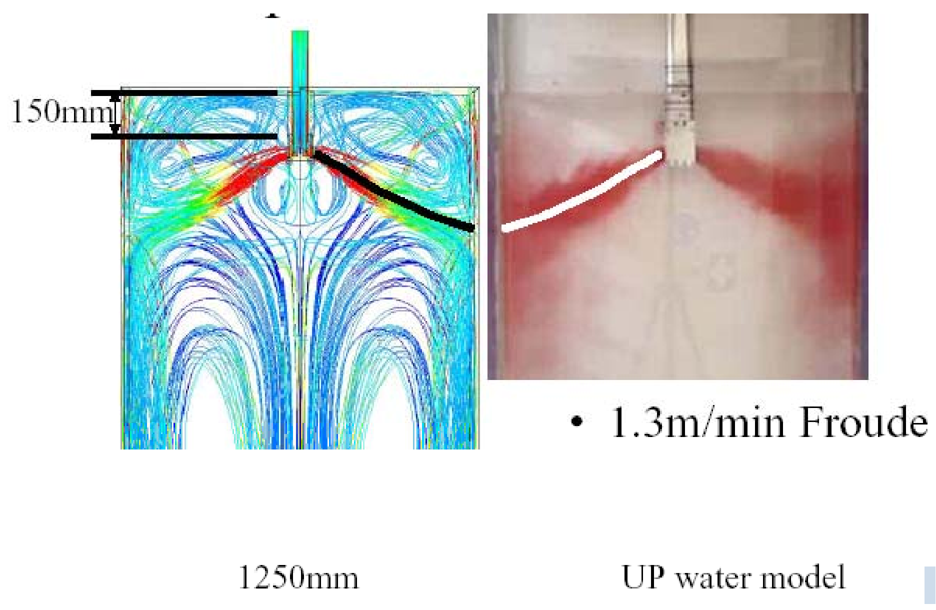
Experiment designation	**Velocity scale [0 – 1 m/s]**	**1250mm width (150mm submergence; 1.3 m/min)**
2.0_linear • angle • port height • well depth • -20º • 80mm • 1mm		

Figure Q.4: Validation of optimum SEN design at 150mm submergence depth, using path lines coloured by velocity magnitude (scale 0 – 1 m/s)