O. <u>Summary: CFD results of best 4 SEN designs of 3D design</u> <u>exploration</u>

O.1 <u>Summary of Results</u>

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 helicity¹ 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 <u>CFD Results: contours of magnitude on symmetry plane (last</u> <u>iterations) and path lines</u>

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 0.15 – 0.21

O.2.4 Experiment 2.0 quadratic

Figures 0.22 – 0.28



O.2.1 Experiment: 1.0

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

Experiment	Helicity scale	1060mm width	1250mm width
designation	$[-0.5 - 0.5 \text{ m/s}^2]$	(80mm submergence; 1.3 m/min)	(80mm submergence; 1.3 m/min)
 angle port height well depth 15° (up) 70mm 0mm 	5.00e-01 4.50e-01 4.00e-01 3.50e-01 3.00e-01 2.50e-01 1.50e-01 1.50e-01 1.00e-01 5.00e-02 2.78e-17 -5.00e-02 -1.00e-01 -1.50e-01 -2.50e-01 -3.00e-01 -4.50e-01 -5.00e-01		

Figure O.2: Contours of helicity on the symmetry plane (range $-0.5 - 0.5 \text{ m/s}^2$)



Figure O.3: Contours of turbulent kinetic energy on symmetry plane (range $0 - 0.1 \text{ m}^2/\text{s}^2$)

Experiment	Vorticity scale	1060mm width	1250mm width
designation	$[0-25 \text{ s}^{-1}]$	(80mm submergence; 1.3 m/min)	(80mm submergence; 1.3 m/min)
 angle port height well depth 15° (up) 70mm 0mm 	2.50e+01 2.38e+01 2.25e+01 2.12e+01 2.00e+01 1.88e+01 1.75e+01 1.50e+01 1.38e+01 1.25e+01 1.12e+01 1.00e+01 8.75e+00 7.50e+00 6.25e+00 5.00e+00		
	3.75e+00 2.50e+00 1.25e+00 0.00e+00		

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

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Experiment	Shear stress	1060mm width	1250mm width
designation	scale	(80mm submergence; 1.3 m/min)	(80mm submergence; 1.3 m/min)
	[0 – 10 Pa]		
 angle port height well depth 15° (up) 70mm 0mm 	1.00e+01 9.50e+00 9.00e+00 8.50e+00 8.00e+00 7.50e+00 6.50e+00 6.00e+00 5.50e+00 4.50e+00 4.50e+00 3.00e+00 2.50e+00 2.50e+00 1.50e+00 1.00e+00 5.00e-01 0.00e+00		

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

Experiment	Temp. scale	1060mm width	1250mm width
designation	[1723 – 1758 K]	(80mm submergence; 1.3 m/min)	(80mm submergence; 1.3 m/min)
 angle port height well depth 15° (up) 70mm 0mm 	1.76e+03 1.76e+03 1.75e+03 1.75e+03 1.75e+03 1.75e+03 1.75e+03 1.75e+03 1.75e+03 1.74e+03 1.74e+03 1.74e+03 1.74e+03 1.74e+03 1.74e+03 1.73e+03 1.73e+03 1.73e+03 1.72e+03 1.72e+03		



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

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O.2.2 <u>Experiment: 1.7</u>



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

Experiment	Helicity scale	1060mm width	1250mm width
designation	$[-0.5 - 0.5 \text{ m/s}^2]$	(80mm submergence; 1.3 m/min)	(80mm submergence; 1.3 m/min)
 angle port height well depth -12.9° 69.9mm 8.9mm 	5.00e-01 4.50e-01 4.00e-01 3.50e-01 3.00e-01 2.50e-01 1.50e-01 1.50e-01 1.00e-01 5.00e-02 2.78e-17 -5.00e-02 -1.00e-01 -1.50e-01 -2.50e-01 -3.00e-01 -3.50e-01 -4.50e-01 -5.00e-01		

Figure O.9: Contours of helicity on the symmetry plane (range $-0.5 - 0.5 \text{ m/s}^2$)



Figure O.10: Contours of turbulent kinetic energy on symmetry plane (range $0 - 0.1 \text{ m}^2/\text{s}^2$)

Experiment	Vorticity scale	1060mm width	1250mm width
designation	$[0-25 \text{ s}^{-1}]$	(80mm submergence; 1.3 m/min)	(80mm submergence; 1.3 m/min)
 angle port height well depth -12.9° 69.9mm 8.9mm 	2.50e+01 2.38e+01 2.25e+01 2.12e+01 2.00e+01 1.88e+01 1.75e+01 1.50e+01 1.25e+01 1.25e+01 1.00e+01 8.75e+00 7.50e+00 5.00e+00 3.75e+00 2.50e+00 1.25e+00 0.00e+00		

Figure O.11: Contours of vorticity on the symmetry plane (range $0 - 25 \text{ s}^{-1}$)

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Experiment	Shear stress	1060mm width	1250mm width
designation	scale	(80mm submergence; 1.3 m/min)	(80mm submergence; 1.3 m/min)
	[0 – 10 Pa]		
 angle port height well depth -12.9° 69.9mm 8.9mm 	1.00e+01 9.50e+00 9.00e+00 8.50e+00 7.50e+00 7.50e+00 6.50e+00 5.50e+00 5.50e+00 4.50e+00 4.50e+00 3.50e+00 3.50e+00 2.50e+00 1.50e+00 1.50e+00 5.00e-01 0.00e+00		

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

Experiment	Temp. scale	1060mm width	1250mm width
designation	[1723 – 1758 K]	(80mm submergence; 1.3 m/min)	(80mm submergence; 1.3 m/min)
 angle port height well depth -12.9° 69.9mm 8.9mm 	1.76e+03 1.76e+03 1.75e+03 1.75e+03 1.75e+03 1.75e+03 1.75e+03 1.75e+03 1.75e+03 1.74e+03 1.74e+03 1.74e+03 1.74e+03 1.74e+03 1.74e+03 1.74e+03 1.73e+03 1.73e+03 1.73e+03 1.72e+03 1.72e+03		

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



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Figure O.14: Path lines originating from the SEN inlet, coloured by vorticity magnitude (range of vorticity $0 - 25 \text{ s}^{-1}$)

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Experiment Velocity scale 1060mm width 1250mm width designation [0 - 1 m/s](80mm submergence; 1.3 m/min) (80mm submergence; 1.3 m/min) 2.0_linear 1.00e+00 9.50e-01 9.00e-01 angle 8.50e-01 • 8.00e-01 port • 7.50e-01 7.00e-01 height 6.50e-01 well • 6.00e-01 5.50e-01 depth 5.00e-01 4.50e-01 4.00e-01 -20° • 3.50e-01 80mm . 3.00e-01 2.50e-01 • 1mm 2.00e-01 1.50e-01 1.00e-01 5.00e-02 0.00e+00

O.2.3 Experiment: 2.0 linear



Experiment	Helicity scale	1060mm width	1250mm width
designation	$[-0.5 - 0.5 \text{ m/s}^2]$	(80mm submergence; 1.3 m/min)	(80mm submergence; 1.3 m/min)
 2.0_linear angle port height well depth -20° 80mm 1mm 	5.00e-01 4.50e-01 4.00e-01 3.50e-01 3.00e-01 2.50e-01 1.50e-01 1.50e-01 5.00e-02 2.78e-17 -5.00e-02 -1.00e-01 -1.50e-01 -2.50e-01 -3.50e-01 -4.00e-01 -4.50e-01 -5.00e-01		

Figure O.16: Contours of helicity on the symmetry plane (range $-0.5 - 0.5 \text{ m/s}^2$)



Figure O.17: Contours of turbulent kinetic energy on symmetry plane (range $0 - 0.1 \text{ m}^2/\text{s}^2$)

Experiment	Vorticity scale	1060mm width	1250mm width
designation	$[0-25 \text{ s}^{-1}]$	(80mm submergence; 1.3 m/min)	(80mm submergence; 1.3 m/min)
 2.0_linear angle port height well depth -20° 80mm 1mm 	2.50e+01 2.38e+01 2.25e+01 2.00e+01 1.88e+01 1.75e+01 1.50e+01 1.38e+01 1.25e+01 1.25e+01 1.12e+01 1.00e+01 8.75e+00 7.50e+00 6.25e+00 3.75e+00 2.50e+00		
	1.25e+00 0.00e+00		

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

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

Experiment	Temp. scale	1060mm width	1250mm width
designation	[1723 – 1758 K]	(80mm submergence; 1.3 m/min)	(80mm submergence; 1.3 m/min)
 2.0_linear angle port height well depth -20° 80mm 1mm 	1.76e+03 1.76e+03 1.75e+03 1.75e+03 1.75e+03 1.75e+03 1.75e+03 1.75e+03 1.75e+03 1.75e+03 1.74e+03 1.74e+03 1.74e+03 1.74e+03 1.74e+03 1.74e+03 1.74e+03 1.73e+03 1.73e+03 1.73e+03 1.72e+03 1.72e+03 1.72e+03		

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



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





O.2.4 Experiment: 2.0 quadratic



Experiment	Helicity scale	1060mm width	1250mm width
designation	$[-0.5 - 0.5 \text{ m/s}^2]$	(80mm submergence; 1.3 m/min)	(80mm submergence; 1.3 m/min)
 2.0_quadratic angle port height well depth -20° 55.5mm 40mm 	5.00e-01 4.50e-01 4.00e-01 3.50e-01 2.50e-01 2.50e-01 2.00e-01 1.50e-01 1.00e-01 5.00e-02 2.78e-17 -5.00e-02 -1.00e-01 -2.50e-01 -3.00e-01 -3.50e-01 -4.50e-01 -5.00e-01		





Figure O.24: Contours of turbulent kinetic energy on symmetry plane (range $0 - 0.1 \text{ m}^2/\text{s}^2$)

Experiment	Vorticity scale	1060mm width	1250mm width
designation	$[0-25 \text{ s}^{-1}]$	(80mm submergence; 1.3 m/min)	(80mm submergence; 1.3 m/min)
 2.0_quadratic angle port height well depth -20° 55.5mm 40mm 	2.50e+01 2.38e+01 2.25e+01 2.12e+01 2.00e+01 1.88e+01 1.75e+01 1.50e+01 1.38e+01 1.25e+01 1.25e+01 1.12e+01 1.00e+01 8.75e+00 5.00e+00 3.75e+00 2.50e+00 0.00e+00		

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

Experiment Shear stress 1060mm width 1250mm width designation scale (80mm submergence; 1.3 m/min) (80mm submergence; 1.3 m/min) [0 – 10 Pa] 2.0_quadratic 1.00e+01 9.50e+00 9.00e+00 angle 8.50e+00 • 8.00e+00 port height • 7.50e+00 7.00e+00 well depth 6.50e+00 6.00e+00 5.50e+00 -20° • 5.00e+00 55.5mm 4.50e+00 4.00e+00 40mm 3.50e+00 3.00e+00 2.50e+00 2.00e+00 1.50e+00 1.00e+00 5.00e-01 0.00e+00

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

Experiment	TemO. scale	1060mm width	1250mm width
designation	[1723 – 1758 K]	(80mm submergence; 1.3 m/min)	(80mm submergence; 1.3 m/min)
 2.0_quadratic angle port height well depth -20° 55.5mm 40mm 	1.76e+03 1.76e+03 1.75e+03 1.75e+03 1.75e+03 1.75e+03 1.75e+03 1.75e+03 1.75e+03 1.75e+03 1.74e+03 1.74e+03 1.74e+03 1.74e+03 1.74e+03 1.73e+03 1.73e+03 1.73e+03 1.73e+03 1.72e+03 1.72e+03		

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

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

APPENDIX P

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

P.1 <u>General</u>

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-surfaces¹ 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 <u>CFD Results: Iso-surfaces of velocity magnitude coloured by vorticity</u> (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 **TKE** scale 1060mm width 1250mm width designation $[0 - 0.1 \text{ m}^2/\text{s}^2]$ (80mm submergence; 1.3 m/min) (80mm submergence; 1.3 m/min) 1.7 1.00e-01 9.50e-02 9.00e-02 8.50e-02 angle 8.00e-02 7.50e-02 port . 7.00e-02 height 6.50e-02 6.00e-02 well • 5.50e-02 depth 5.00e-02 4.50e-02 4.00e-02 -12.9° . 3.50e-02 3.00e-02 69.9mm 2.50e-02 2.00e-02 8.9mm 1.50e-02 1.00e-02 5.00e-03 0.00e+00

P.2.2 <u>Experiment: 1.7</u>





P.2.3 Experiment: 2.0 linear





P.2.4 Experiment: 2.0 quadratic

Figure P.4: Contours of turbulent kinetic energy on symmetry plane (range $0 - 0.1 \text{ m}^2/\text{s}^2$)

APPENDIX Q

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

Q.1 <u>General</u>

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 <u>Optimum SEN CFD results validation: 80mm and 150mm</u> <u>submergence</u>

Q.2.1 Submergence depth: 80mm Figures Q.1 and Q.2

Q.2.2 <u>Submergence depth: 150mm</u>

Figures Q.3 and Q.4

Appendix Q



Q.2.1 Submergence depth: 80mm



velocity (scale 0 - 1 m/s)

Experiment	Velocity scale	1250mm width	
designation	[0 - 1 m/s]	(80mm submergence; 1.3 m/min)	
 2.0_linear angle port height well depth -20° 80mm 1mm 	1.00e+00 9.50e-01 9.00e-01 8.50e-01 8.50e-01 7.50e-01 7.50e-01 6.50e-01 6.00e-01 5.50e-01 4.50e-01 4.50e-01 3.50e-01 3.50e-01 2.50e-01 1.50e-01	80mm	• 1.3m/min Froude
	1.00e-01 5.00e-02 0.00e+00	1250mm	UP water model



Appendix Q



Q.2.2 Submergence depth: 150mm



velocity (scale 0 - 1 m/s)

Experiment	Velocity scale	1250mm width	
designation	[0 - 1 m/s]	(150mm submergence; 1.3 m/min)	
 2.0_linear angle port height well depth -20° 80mm 1mm 	1.00e+00 9.50e-01 9.00e-01 8.50e-01 8.00e-01 7.50e-01 7.50e-01 6.50e-01 5.50e-01 5.50e-01 4.50e-01 4.50e-01 3.50e-01 2.50e-01 1.50e-01 1.50e-01 5.00e-02	150mm 600 100 100 100 100 100 100 100 100 100	• 1.3m/min Froude
	0.00e+00	12501111	Of water model

