Simulation and Visualisation of Wire-Arc Additive Manufacture

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COMSOL CONFERENCE
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Overview

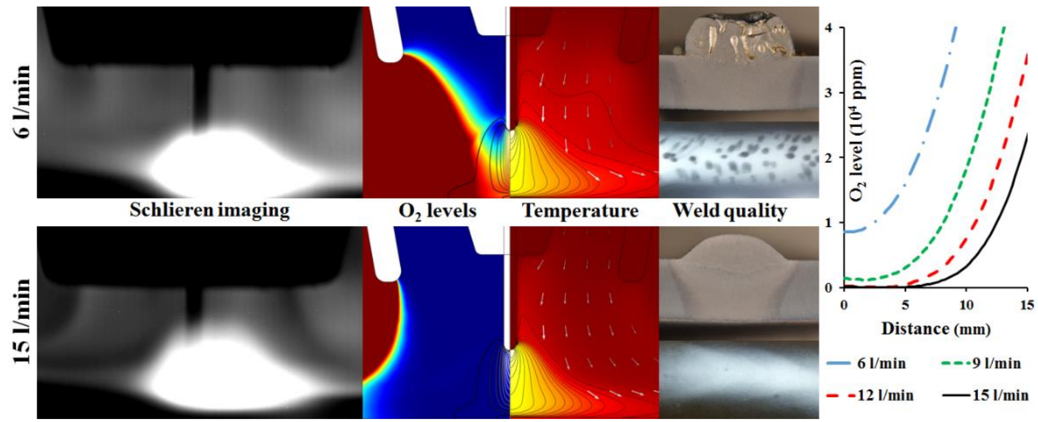
Background
previous work, WAAM process

MHD flow modelling
Plasma arc welding torch model

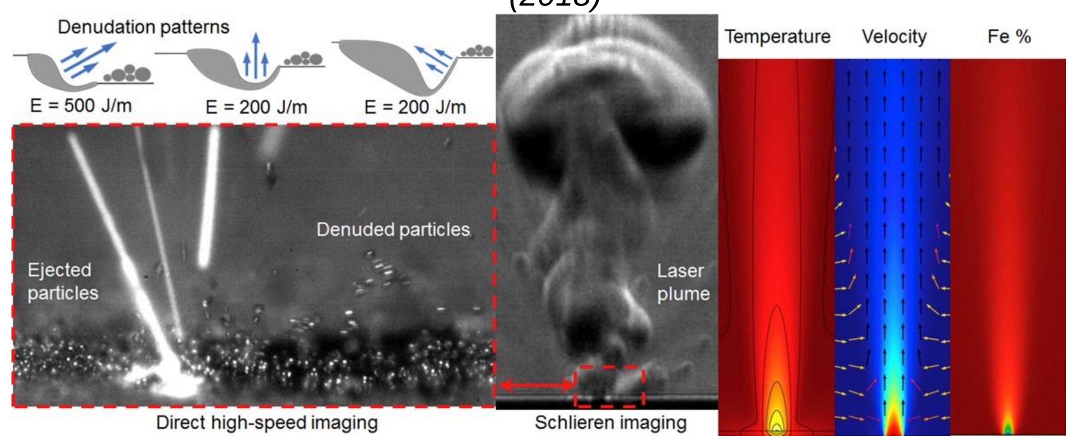
Schlieren imaging
Validation through optical diagnostics

Ongoing work
Trail shield, torch optimisation

Pressure validation



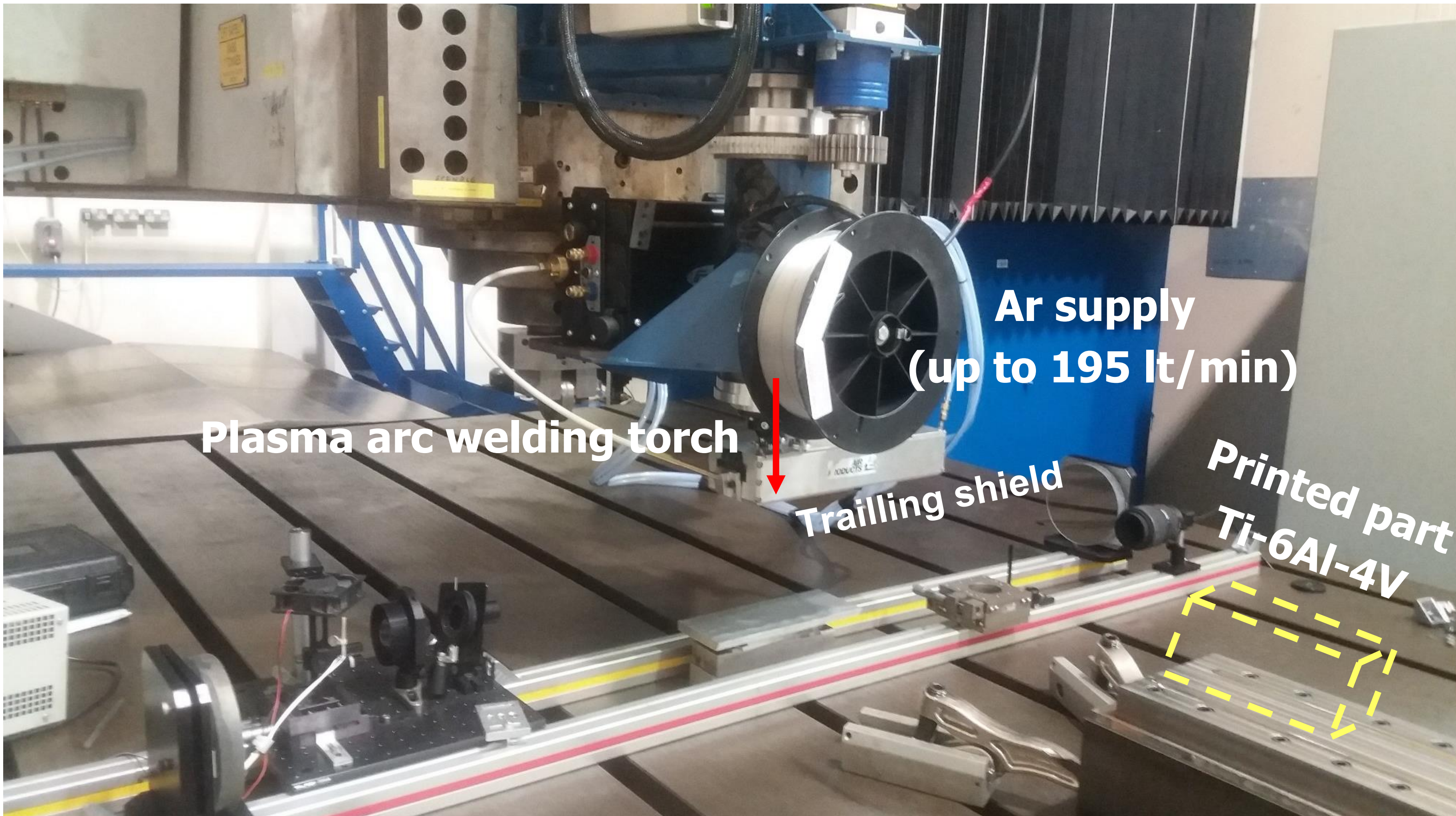
I. Bitharas *et al.*, **Visualisation and optimisation of shielding gas coverage during GMAW**, *Journal of Materials Processing Technology (2018)*



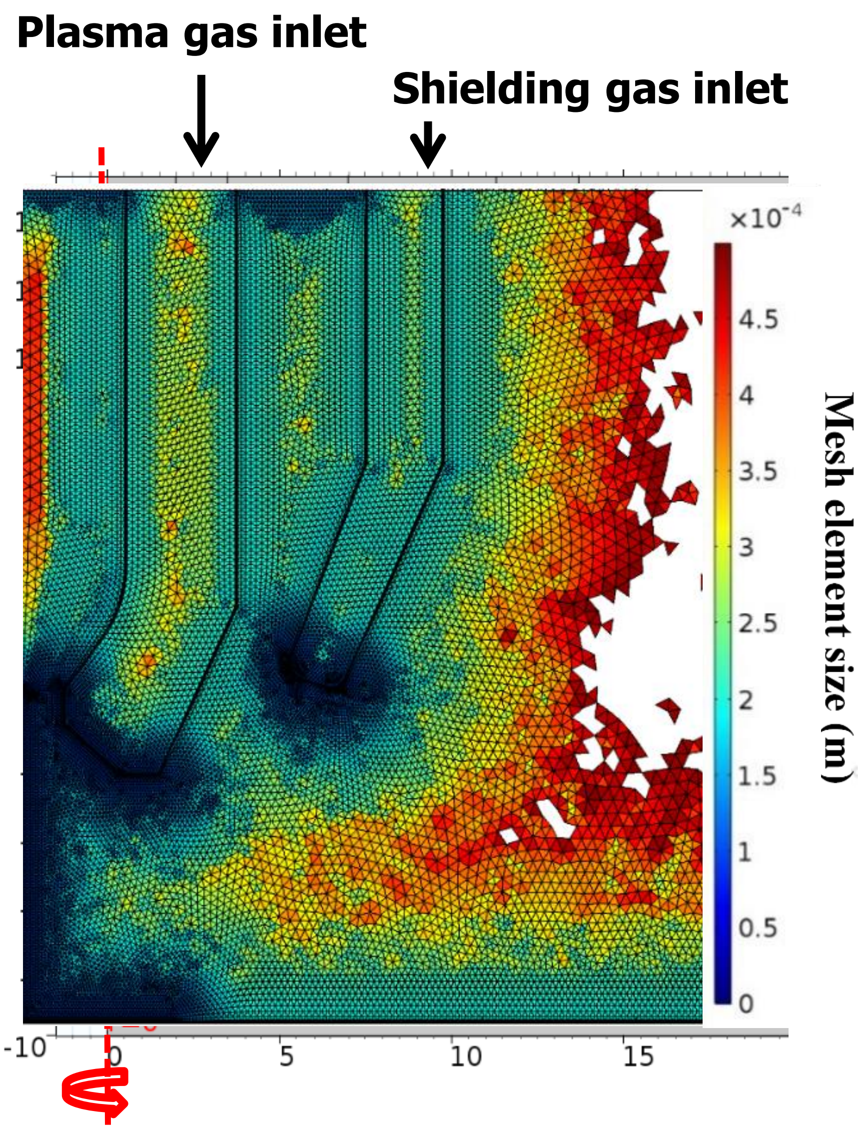
P. Bidare, I. Bitharas *et al.*, **Fluid and particle dynamics in LPBF**, *Acta Materialia 142* (2018)

Wire – Arc Additive Manufacture (WAAM)

HiVE Chamber @ Cranfield University: gantry-based motion



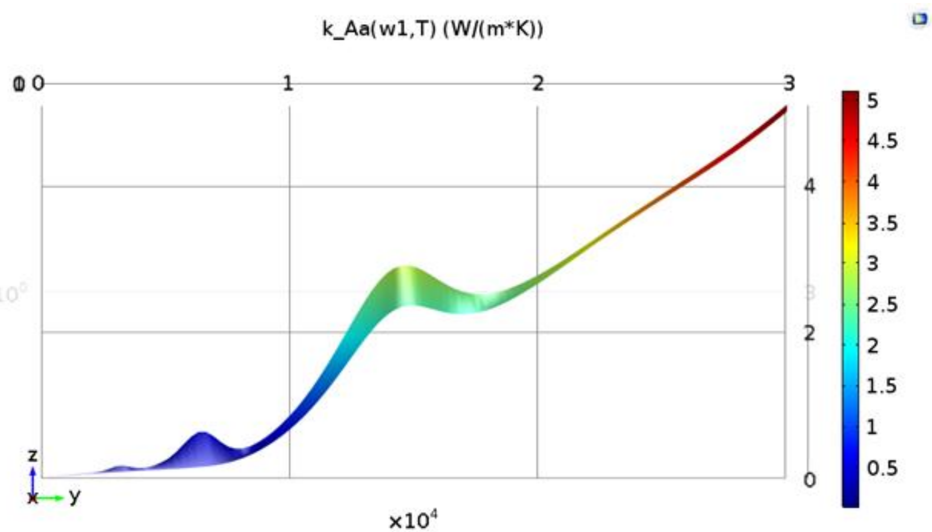
PAW torch simulation layout



Ti-6Al-4V workpiece (Wall/substrate)

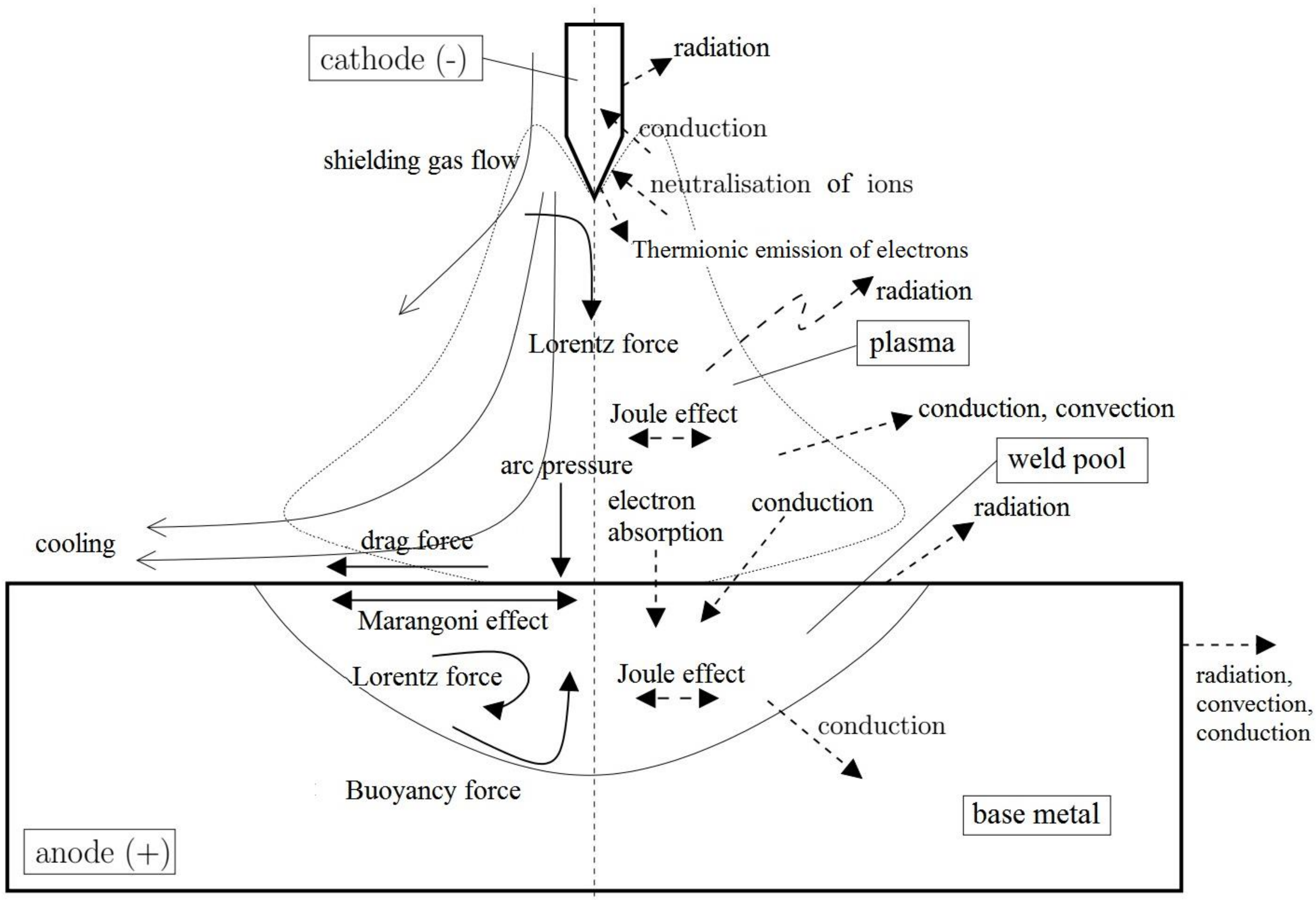
Ar-air thermal plasma in LTE

Highly non-linear multiphysics problem



Ar - air mixture properties $f(T, \omega)$

Plasma arc welding: Magneto-hydrodynamics



Simulating MHD flow with COMSOL

$$\rho(\mathbf{u}\cdot\nabla\mathbf{u}) = \nabla\cdot[-p + \mu(\nabla\mathbf{u} + (\nabla\mathbf{u})^{\mathbf{T}})] + \mathbf{F}$$

$$\nabla\cdot(\rho\mathbf{u}) = 0$$

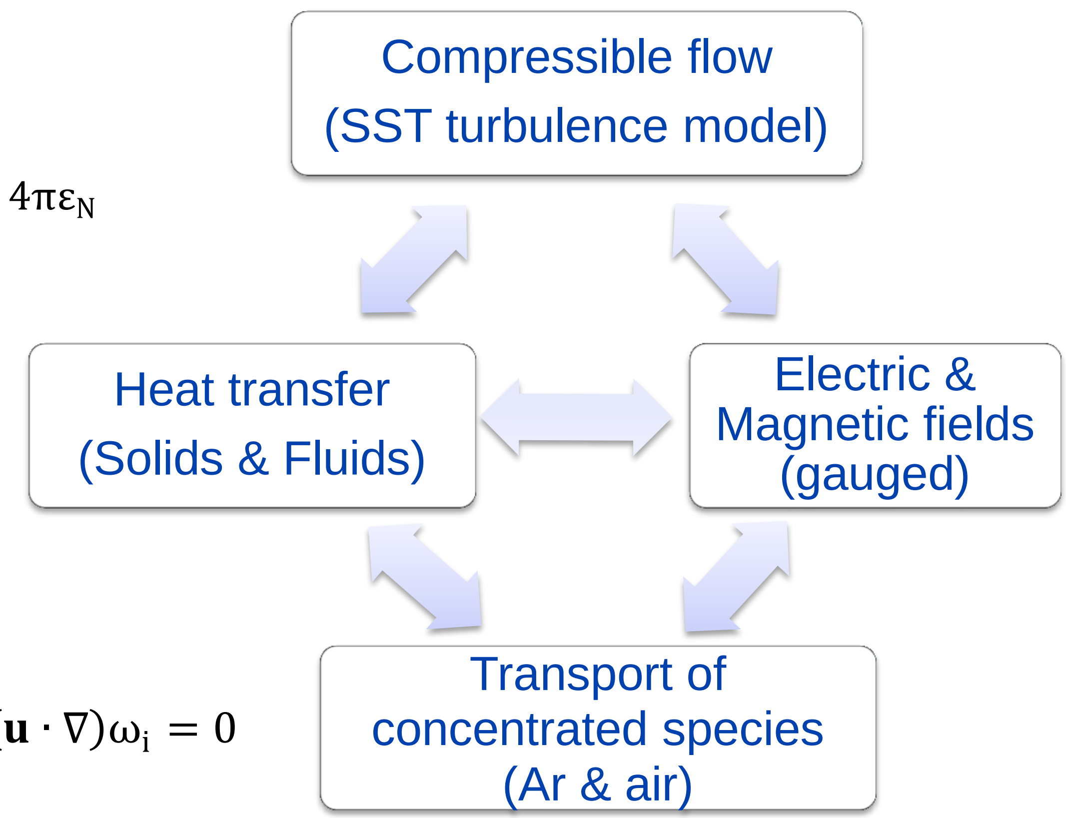
$$-\nabla\cdot(k\nabla T) + \rho c_p(\mathbf{u}\cdot\nabla T) = \mathbf{J}\cdot\mathbf{E} + \frac{5k_b}{2e}\mathbf{J}\cdot\nabla T - 4\pi\varepsilon_N$$

$$\nabla\times\left(\frac{1}{\mu_0}\nabla\times\mathbf{A}\right) + \sigma\nabla V = 0$$

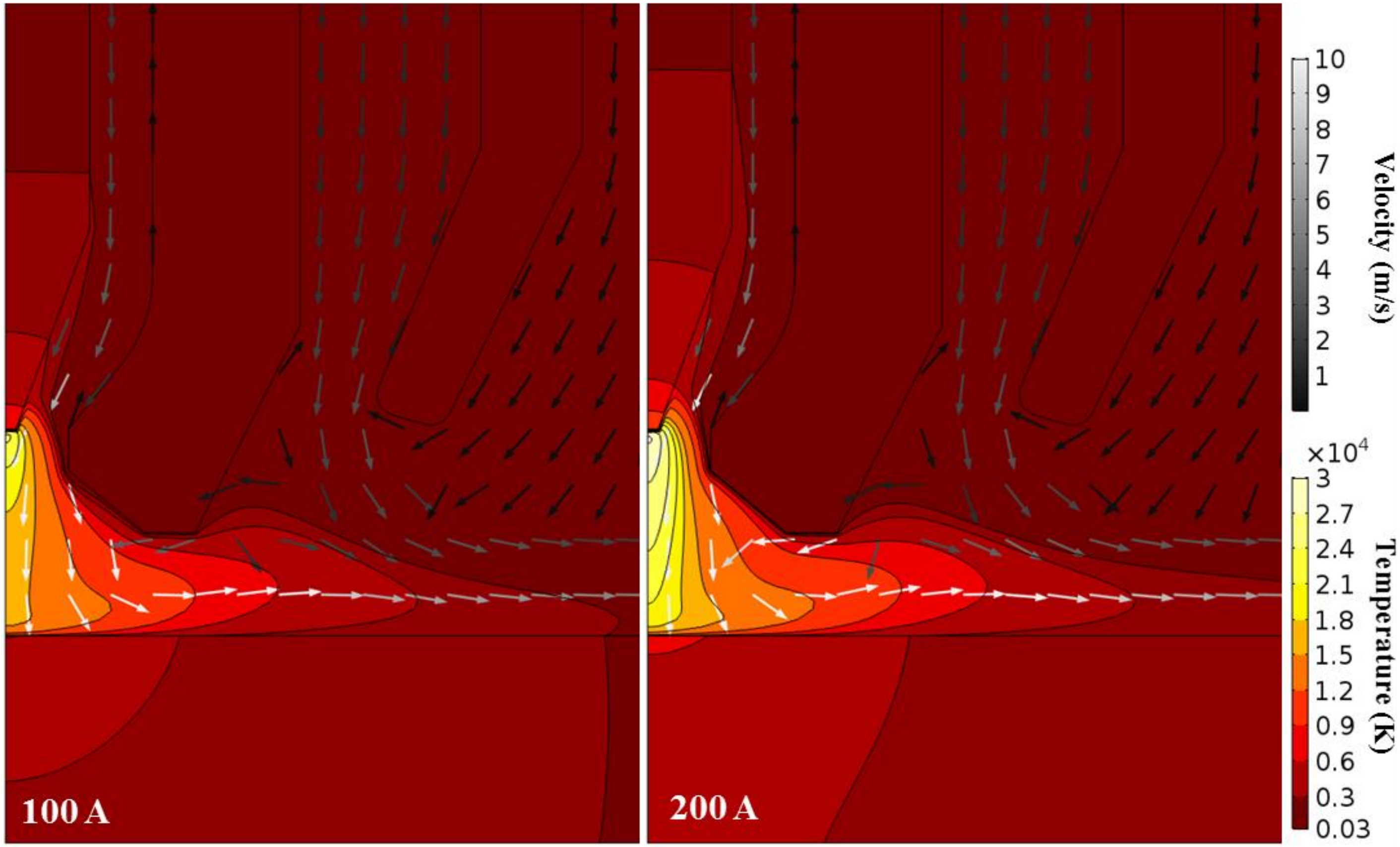
$$\nabla\cdot\sigma\nabla V = 0$$

$$-\nabla\cdot\left(\rho D_i^o\,\nabla\omega_i + \rho\omega_i D_i^o\frac{\nabla M_n}{M_n} + D_i^T\frac{\nabla T}{T}\right) + \rho(\mathbf{u}\cdot\nabla)\omega_i = 0$$

Implicit & explicit physics couplings



Plasma jet – shield gas stream interaction

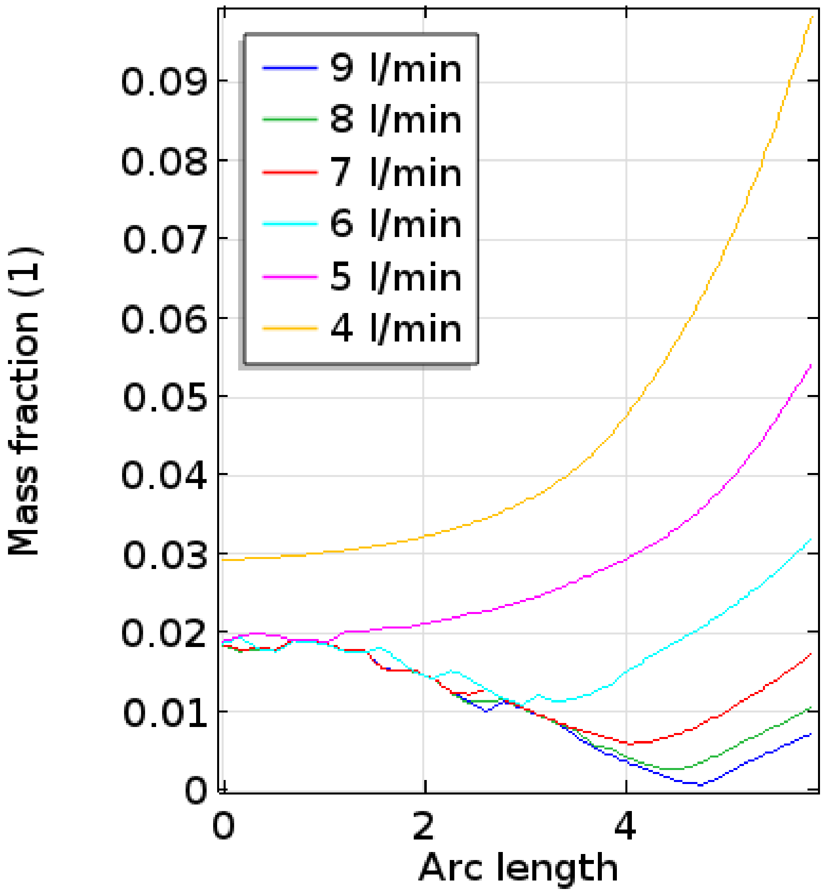


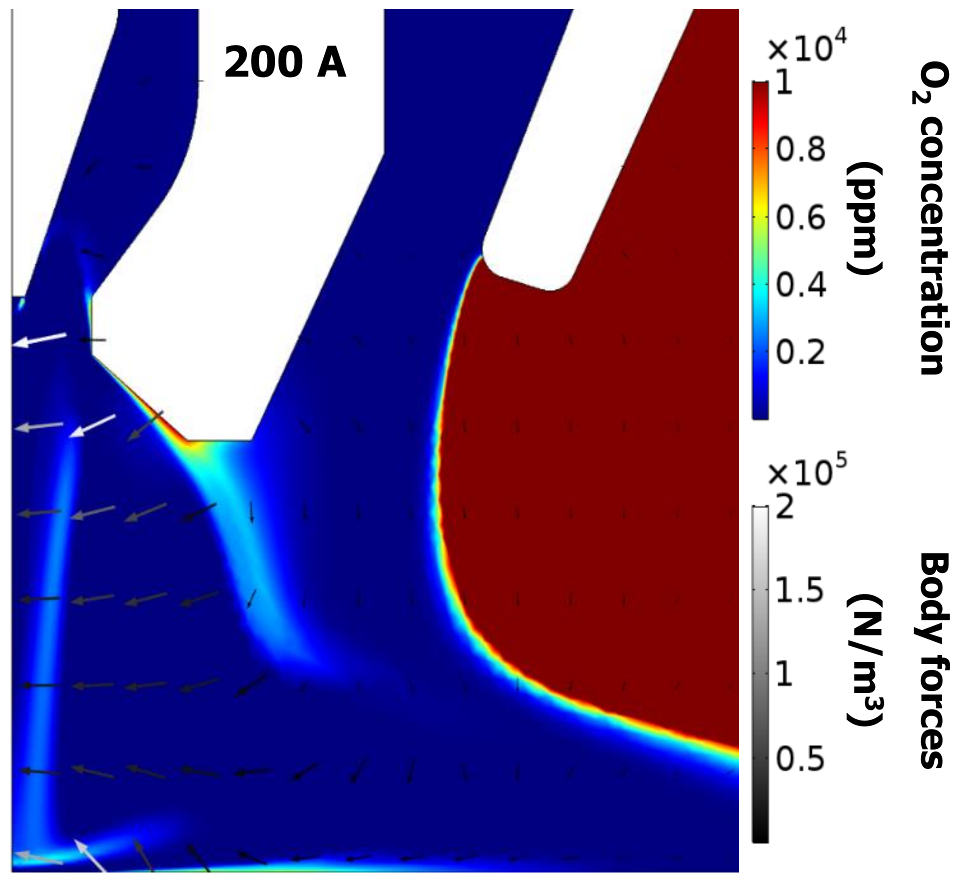
Temperature field partly constricted by nozzle

Arc pinches shield gas flow

Convective recirculation

Steady-state air entrainment



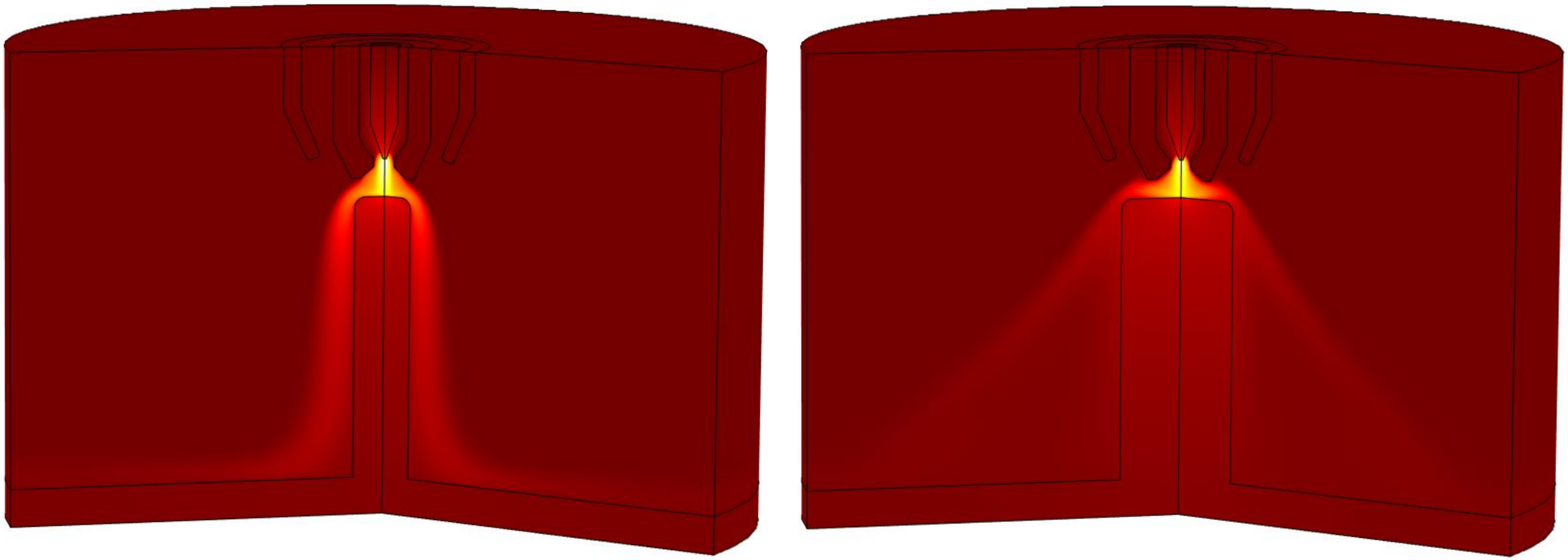


Lorentz force ($F_L = J \times B$) high near electrodes

Stronger pull but similar air levels with higher current

~4k ppm air transported near melt pool (!)

Deposited wall geometry: Temperature

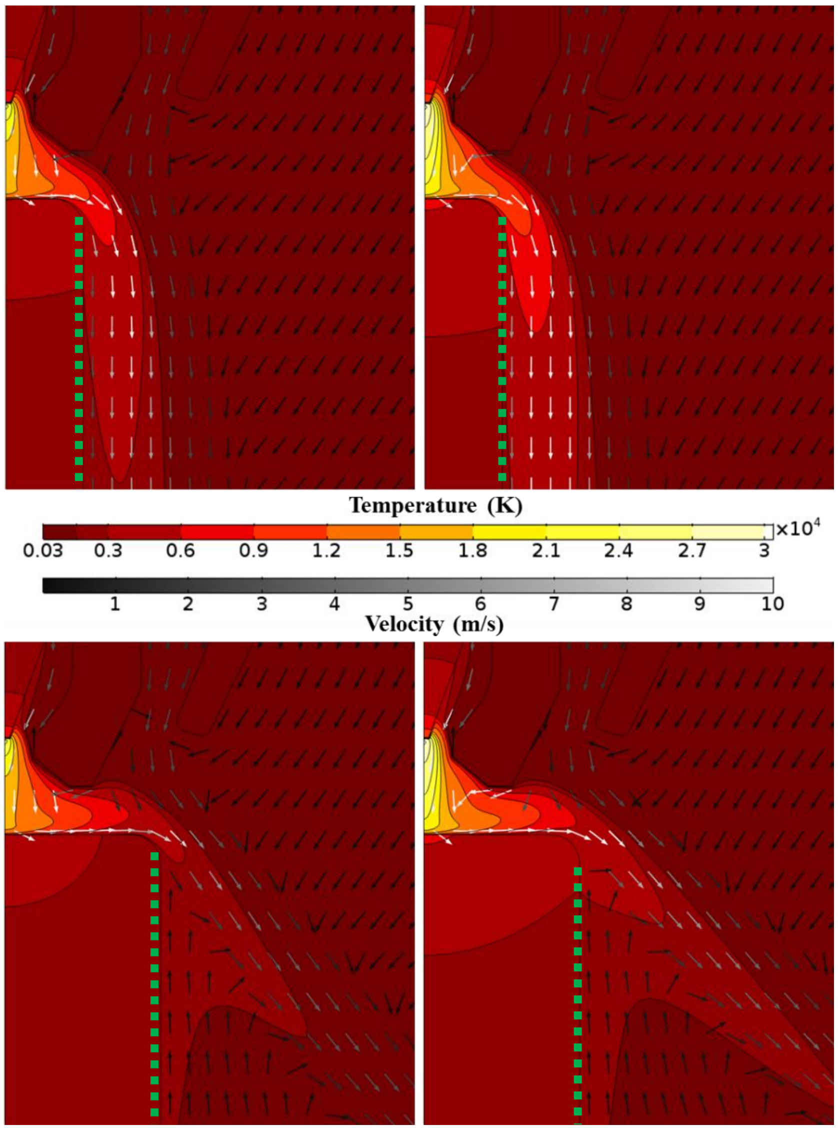


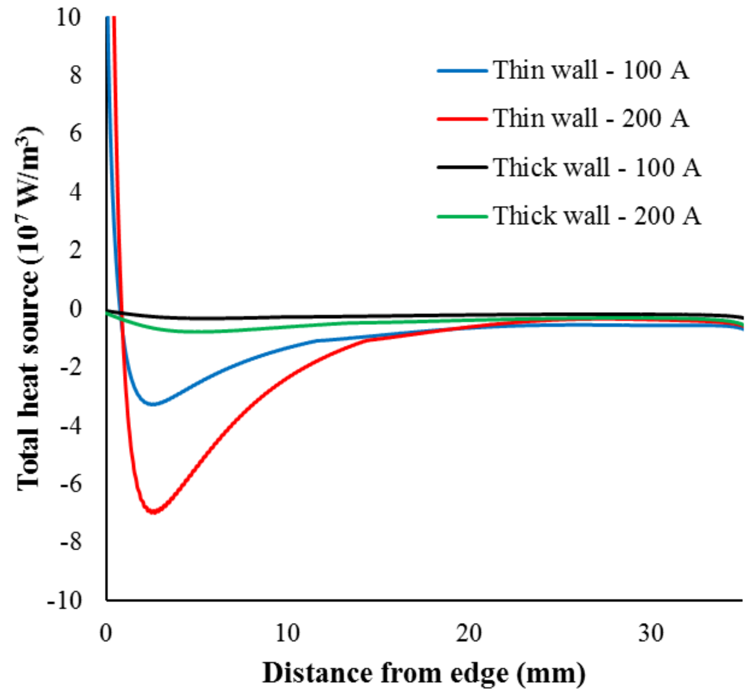
Side jet inclination changes with wall width

Heat transfer to wall influenced by convective action

Also relevant to torch positioning during builds

Heat transfer to wall

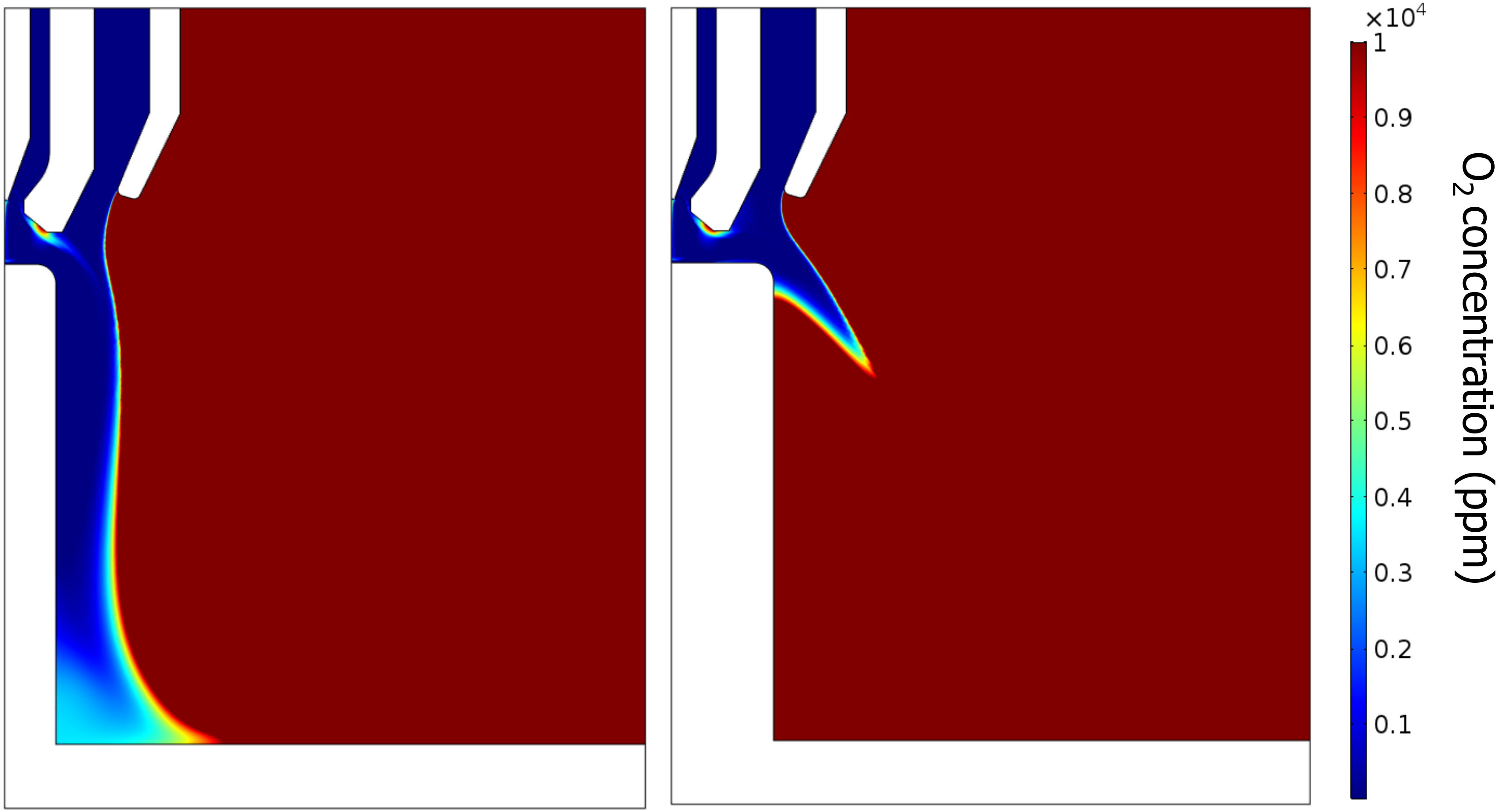




Flow along wall enhances heat transfer

Inner and outer vortex structure

Wall geometry – O_2 concentration



Inert environment changes with wall geometry

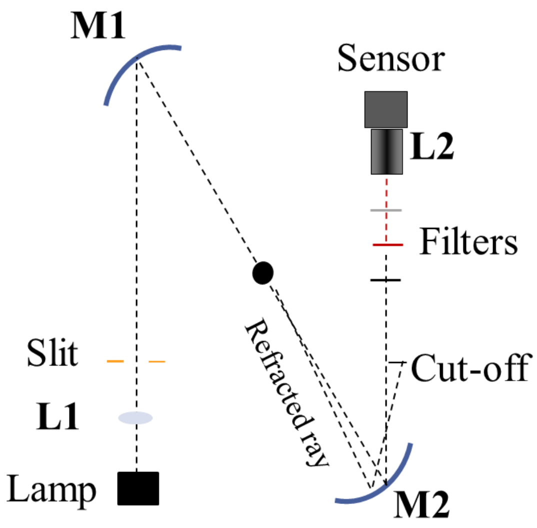
Schlieren imaging

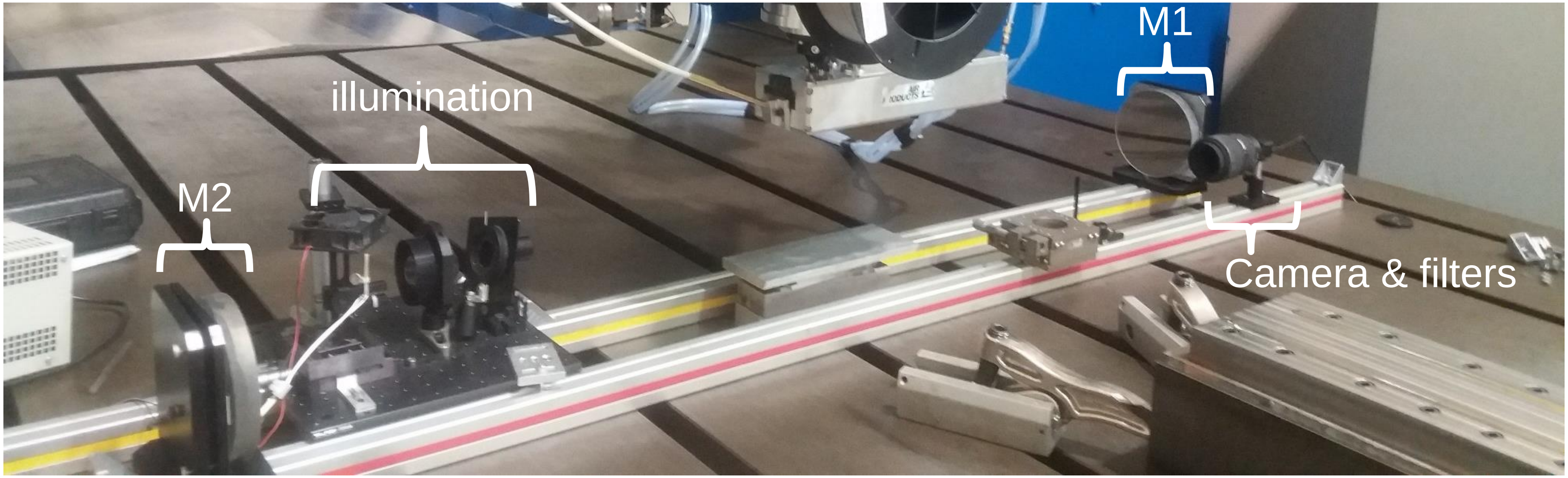
Light collimated between M1 & M2

Flow information = Refracted rays

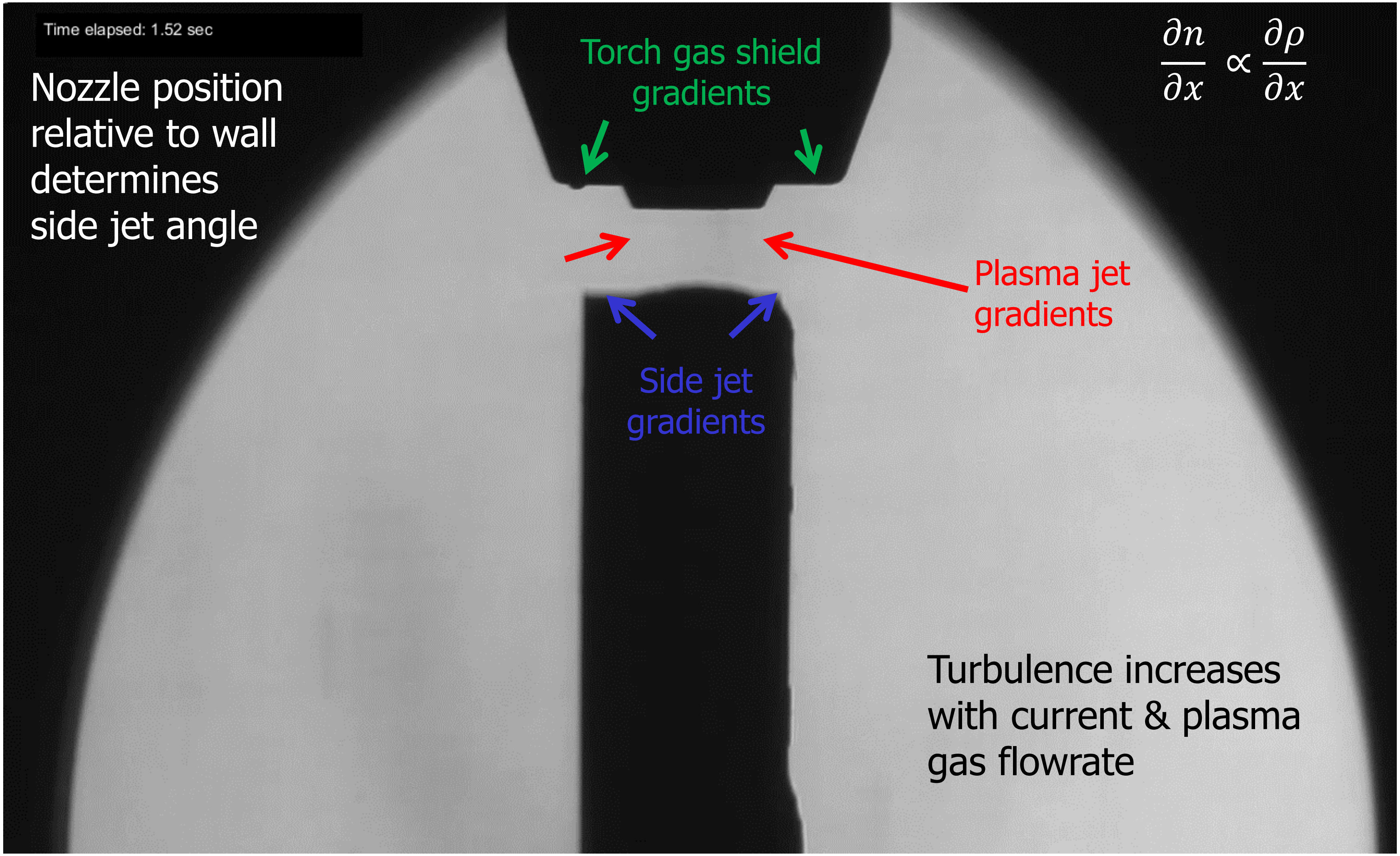
Cut-off highlights $\frac{\partial n}{\partial x} \propto \frac{\partial \rho}{\partial x}$

Band pass filter at 633 ± 10 nm

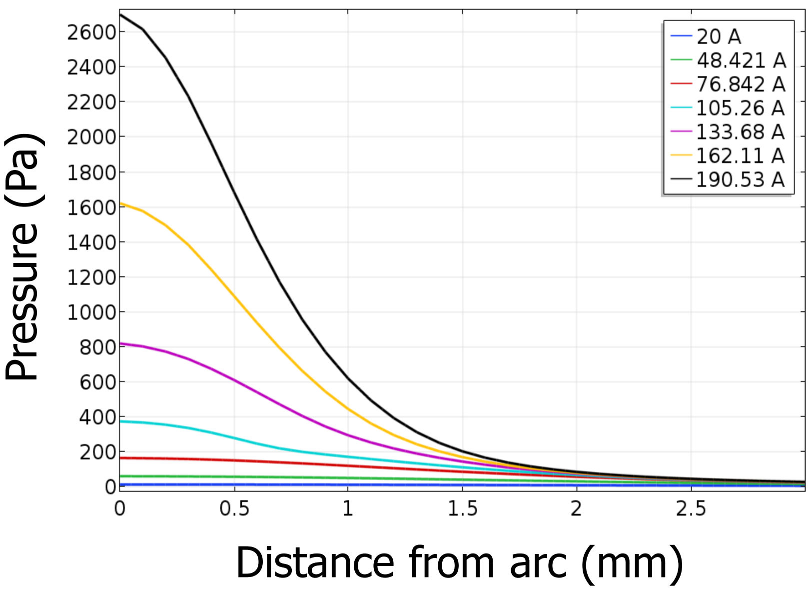


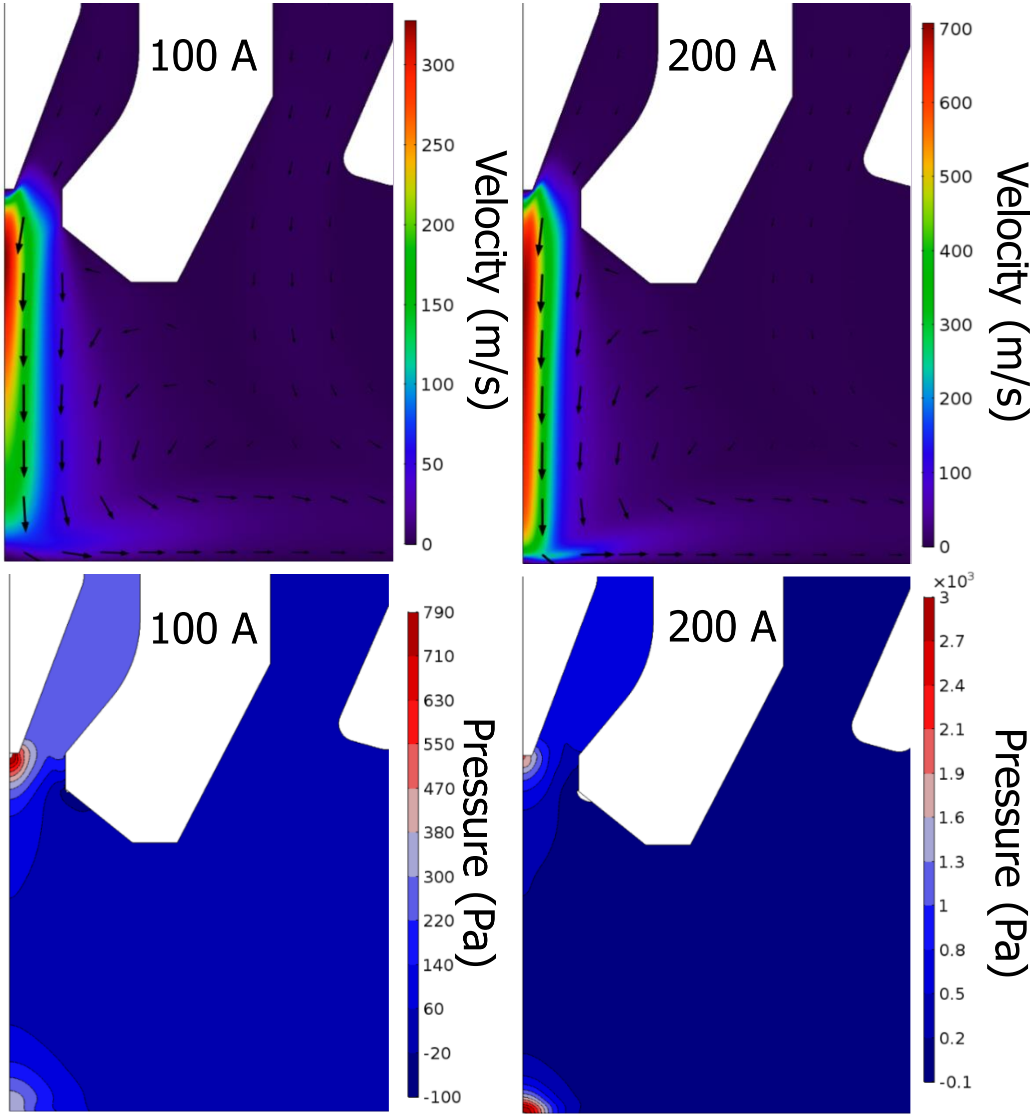


PAW torch – schlieren video



Ongoing work





Pressure measurements to further validate model

Momentum transfer in arc critical in understanding interaction with melt pool

No steady-state level set!

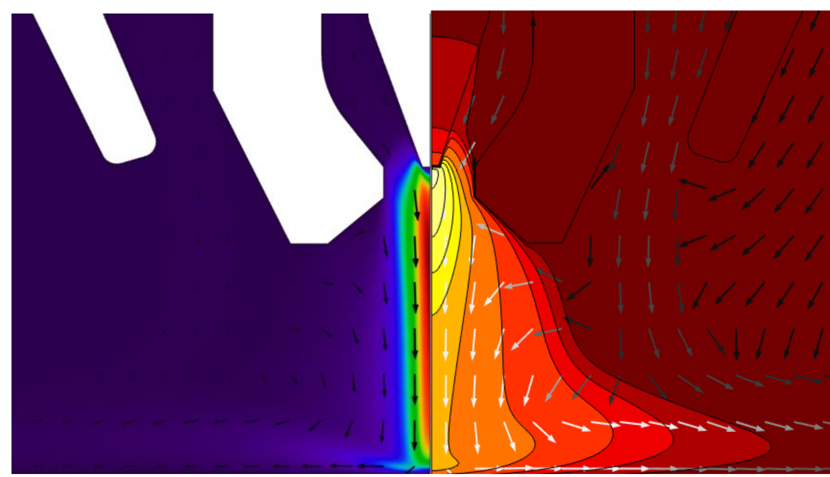
Results summary

MHD flow features validated from schlieren

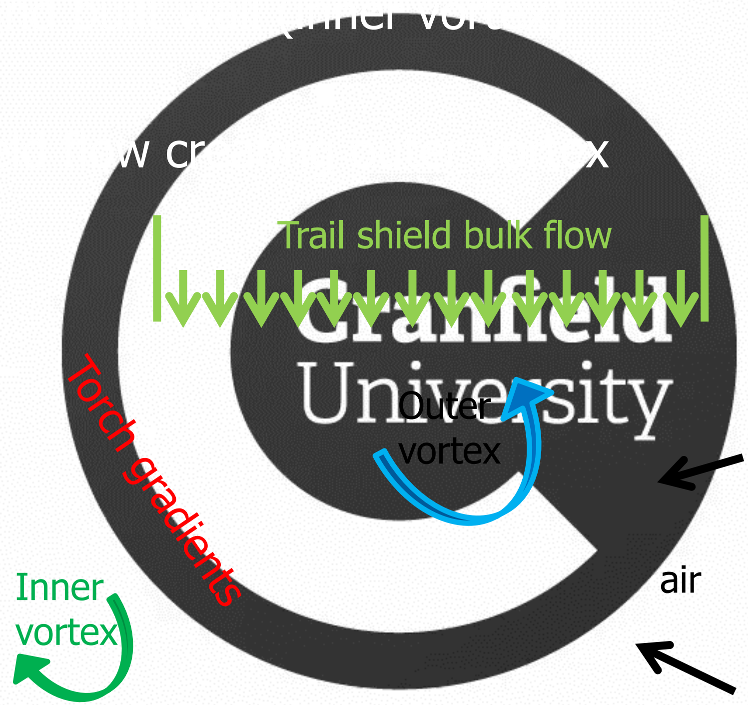
Schlieren interpretation facilitated by simulation

Allows optimisation of WAAM process

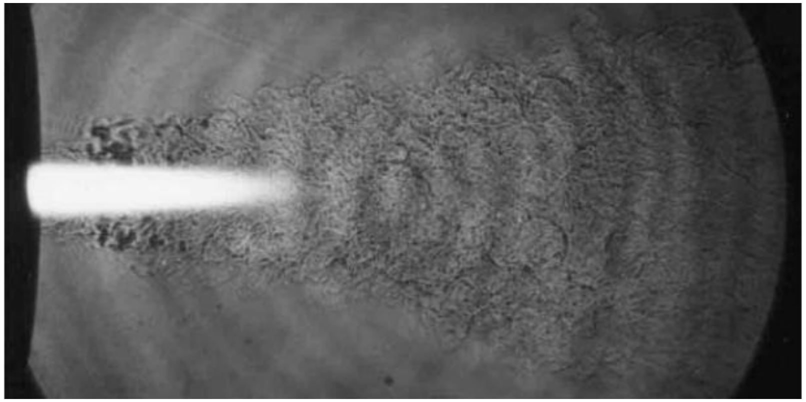
Torch – Shielding – Manufactured part



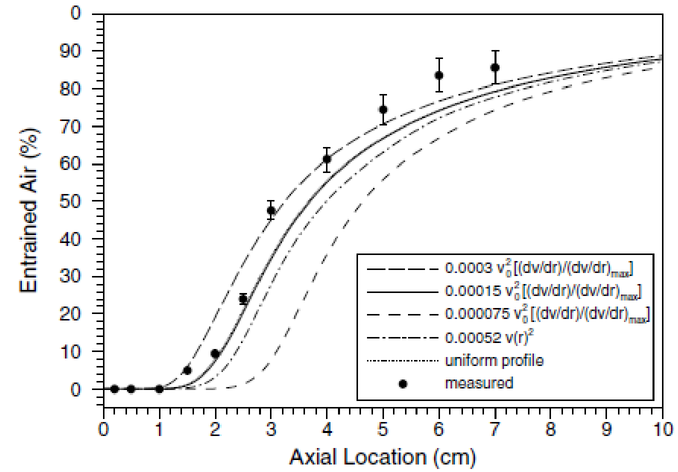
HiVE local shielding system



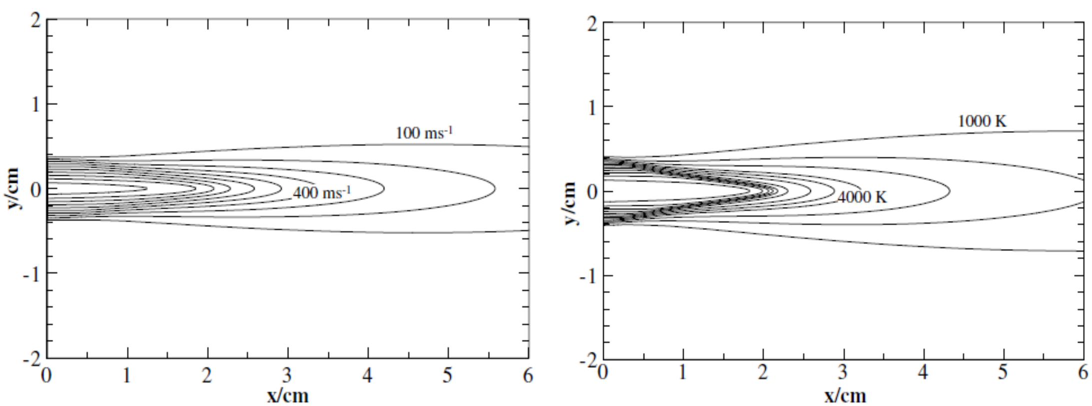
MHD modelling: Turbulent jets

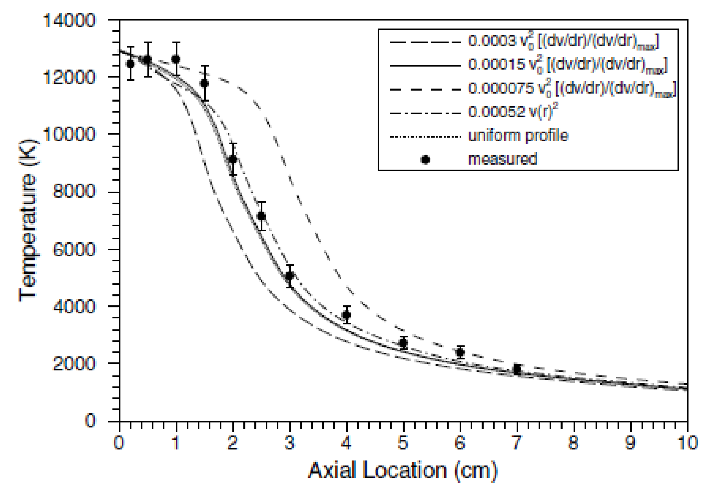


- Enthalpy probes
- Thomson scattering
- Laser-induced fluorescence



Comparison with simulation, including k-ε turbulence model



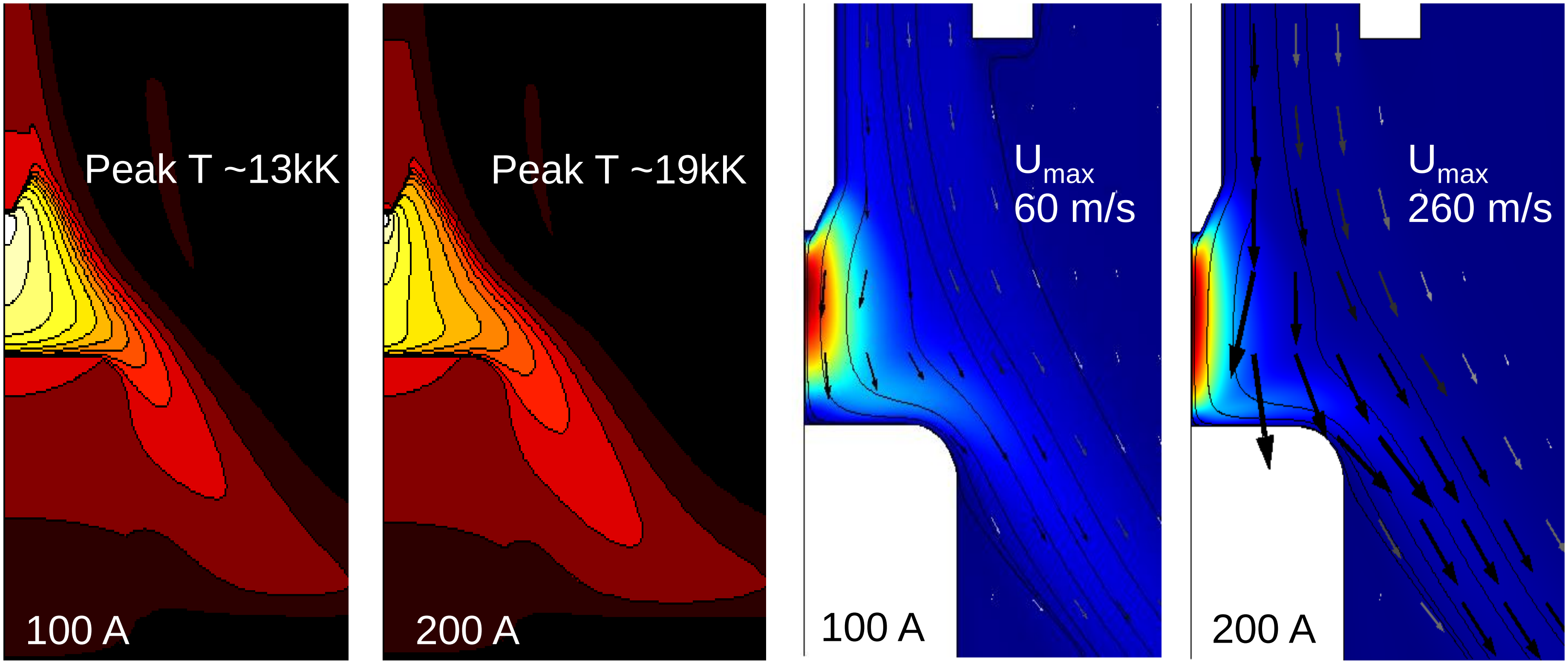


K. Cheng, X. Chen, **Prediction of the entrainment of ambient air into a turbulent argon plasma jet using a turbulence-enhanced combined-diffusion-coefficient method**, Int. J. Heat Mass Transf., 2004

J. R. Fincke, R.L. Williamson, et al. **Entrainment in high-velocity, high-temperature plasma jets. Parts I & II** , Int. J. Heat Mass Transf., 2003

TIG torch in WAAM wall

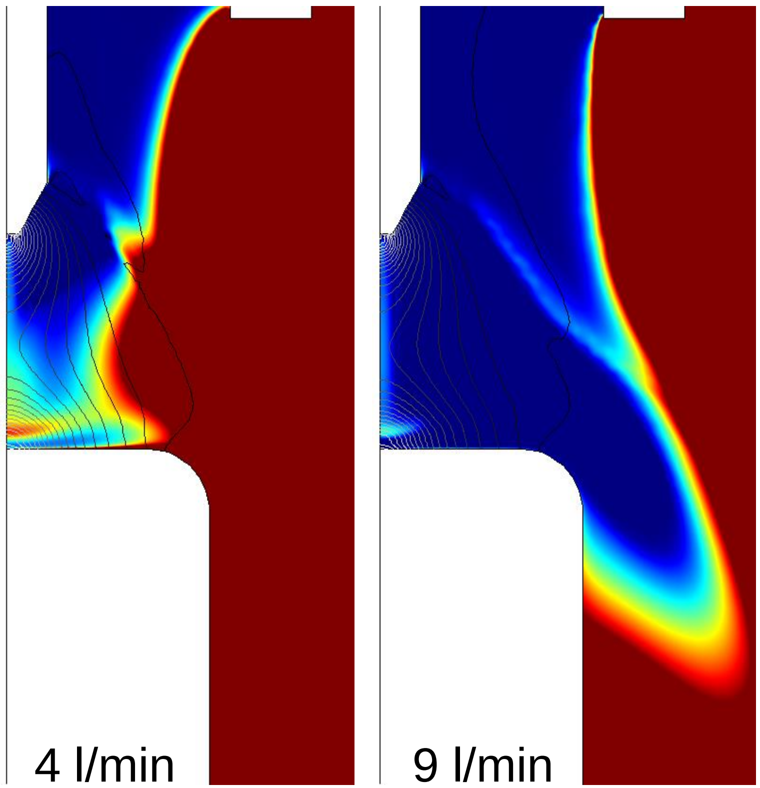
- Step towards more representative plasma torch model
- MHD physics identical with PAW, steady-state flow patterns similar
- 2D axisymmetric geometry: ~15 mins solution time per case

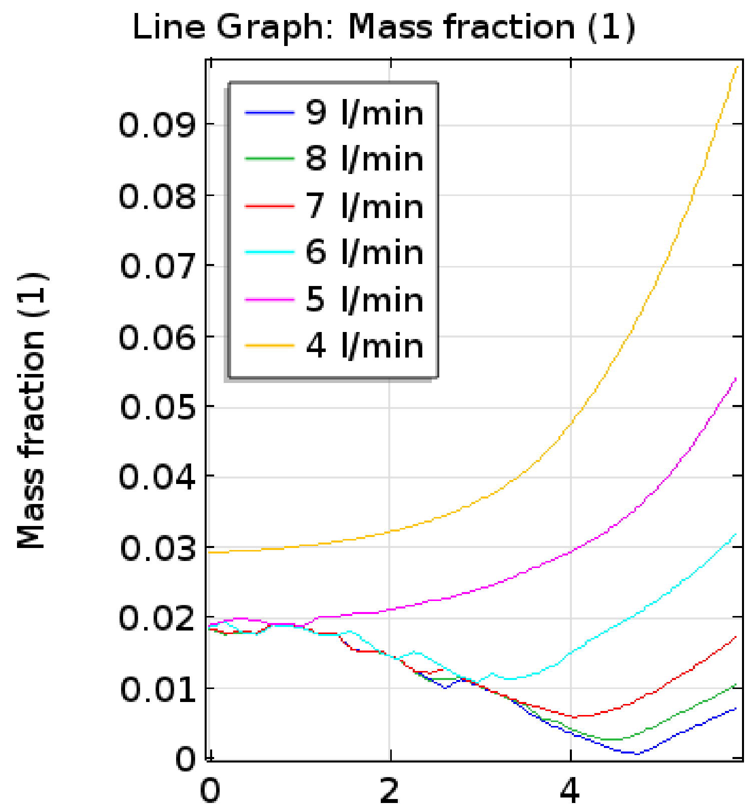


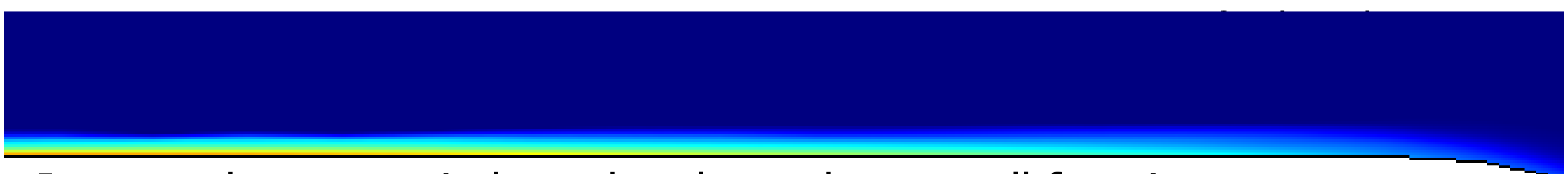
Temperature plot

Velocity plot

Air contamination



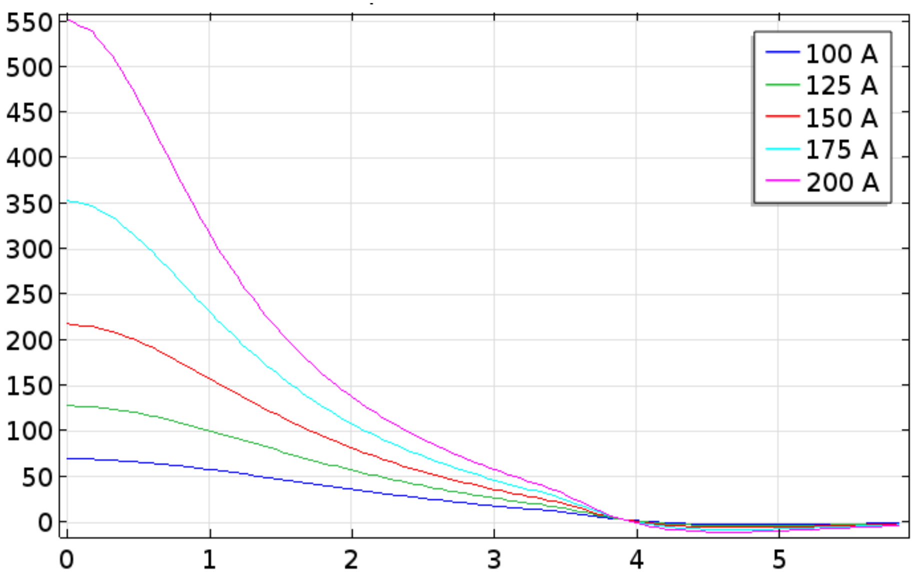




Increased accuracy in boundary layer due to wall functions
(SST turbulence model)

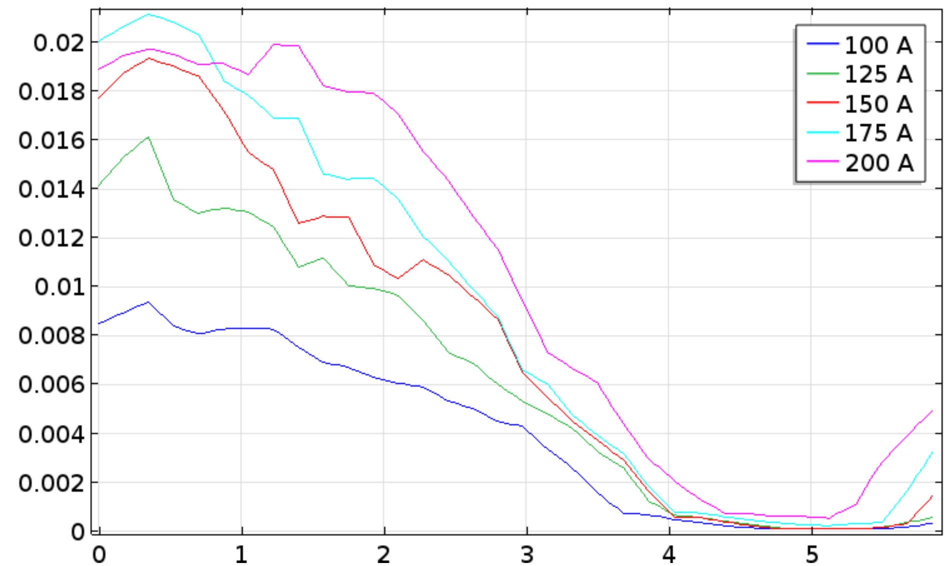
Parametric sweeps

Pressure (Pa)



Distance from arc (mm)

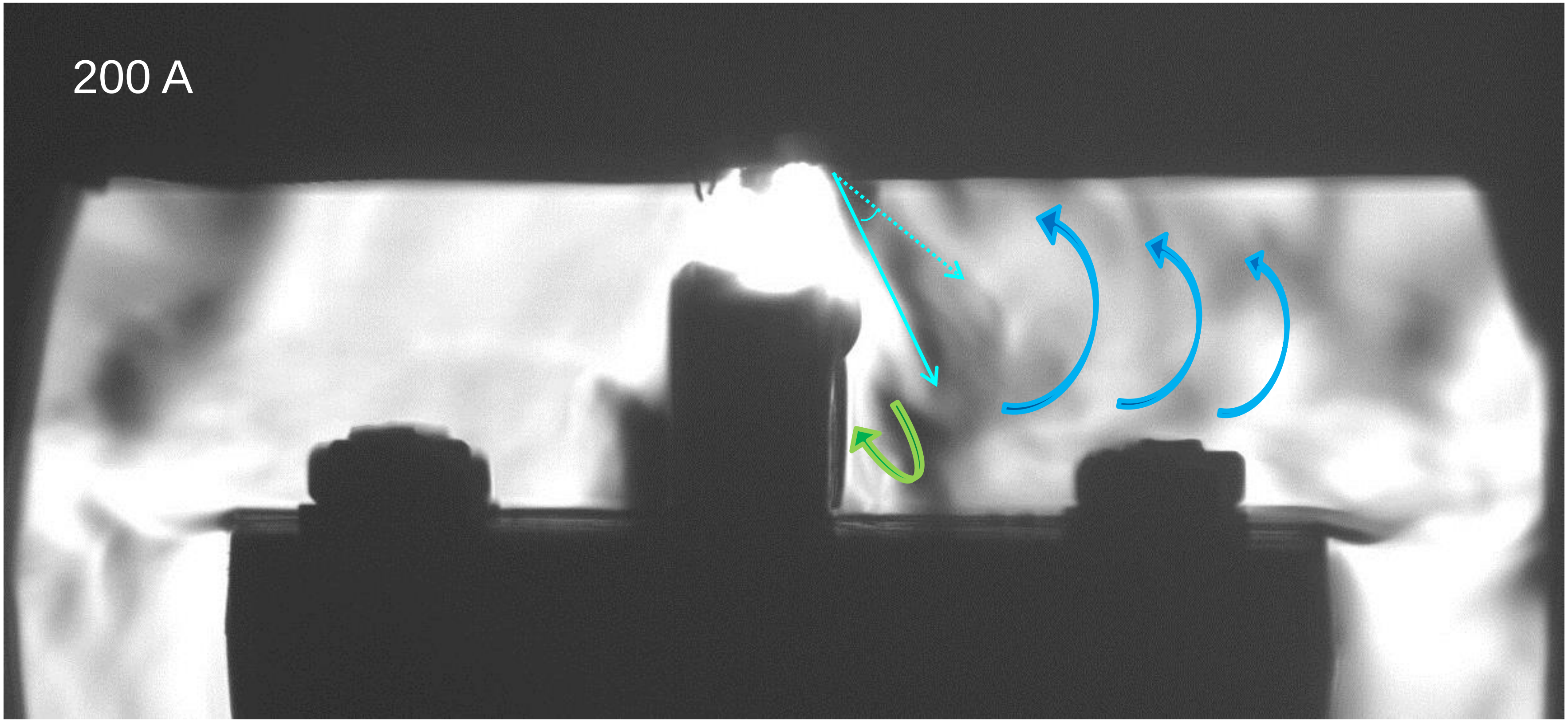
Air mass fraction (1)



Distance from arc (mm)

- Stagnation pressure increases non-linearly with arc current
- Air entrainment doubled for 200 A compared to 100 A
- Theoretical analyses to complement future measurements

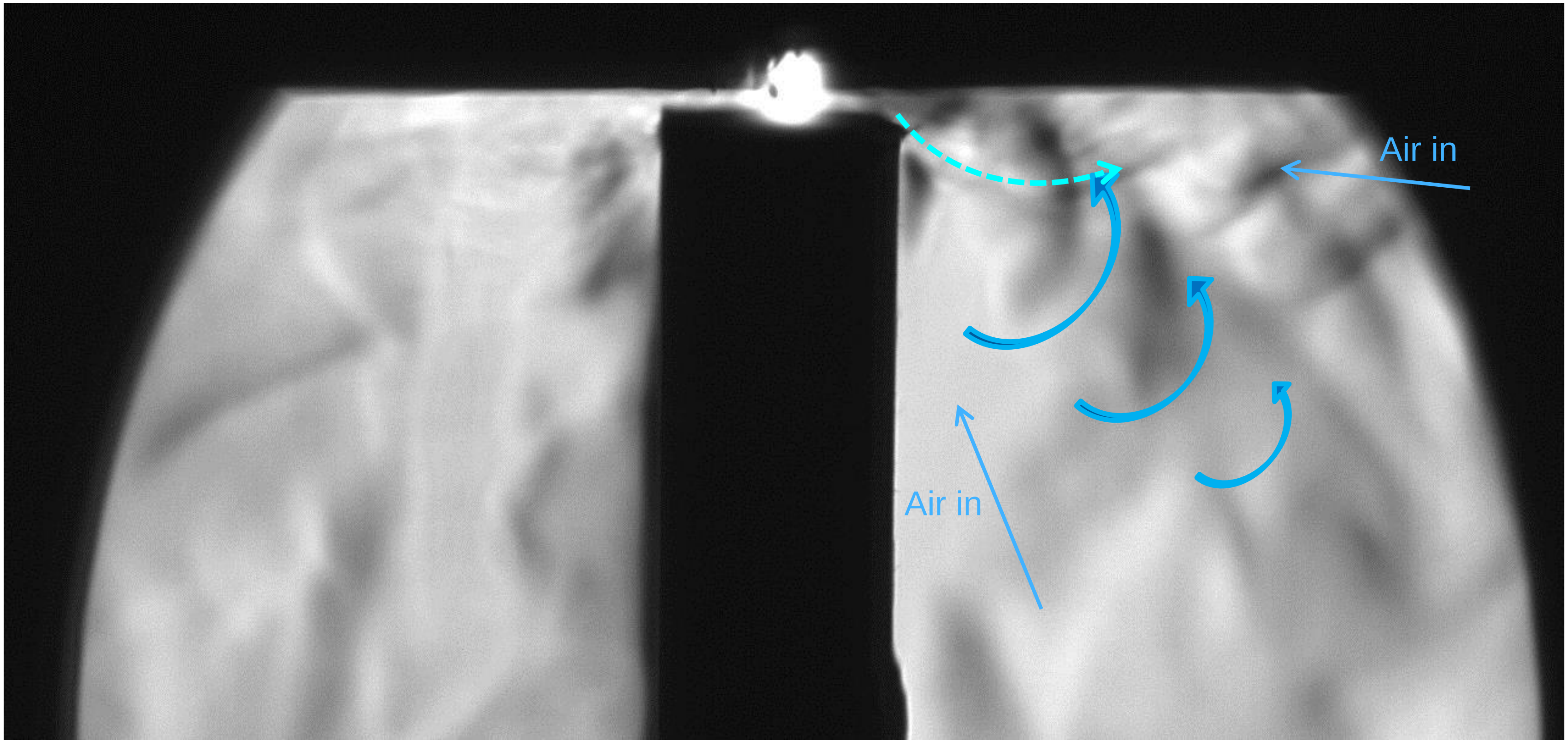
Turbulence intensity



- As current increases, the side jets contract but also push out and downwards with more momentum
- Overall greater turbulence levels
- Relatively higher air content on top of solidifying metal expected

Rv: torch + trail shield/PAW_trail_shield_7

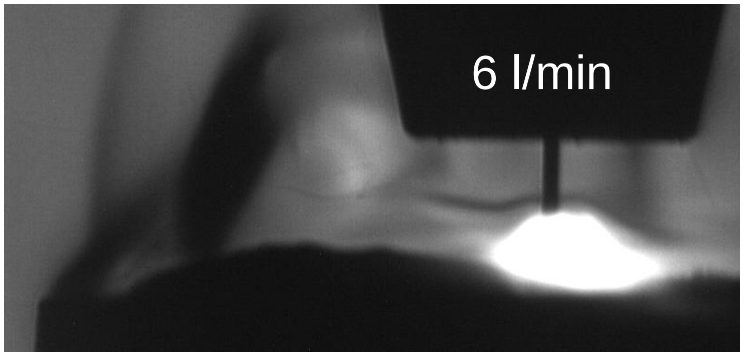
The high wall problem

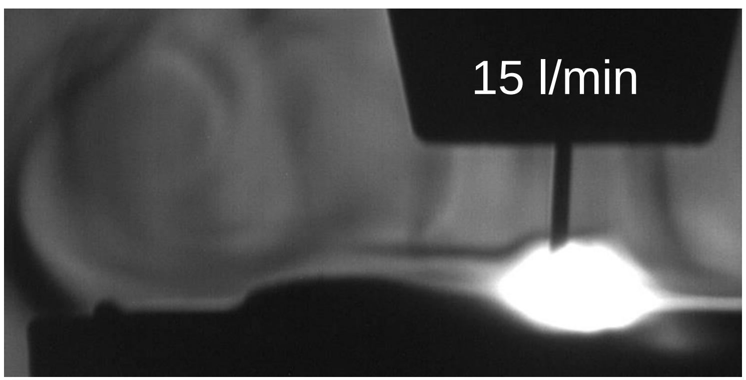


- As the physical constraint of the substrate is no longer there, the inner area becomes more exposed
- The outer vortex stretches to the extent that it loses effectiveness
- Air contamination increases proportionally to standoff <u>from substrate</u>

Rv: torch + trail shield/PAW_trail_shield_9

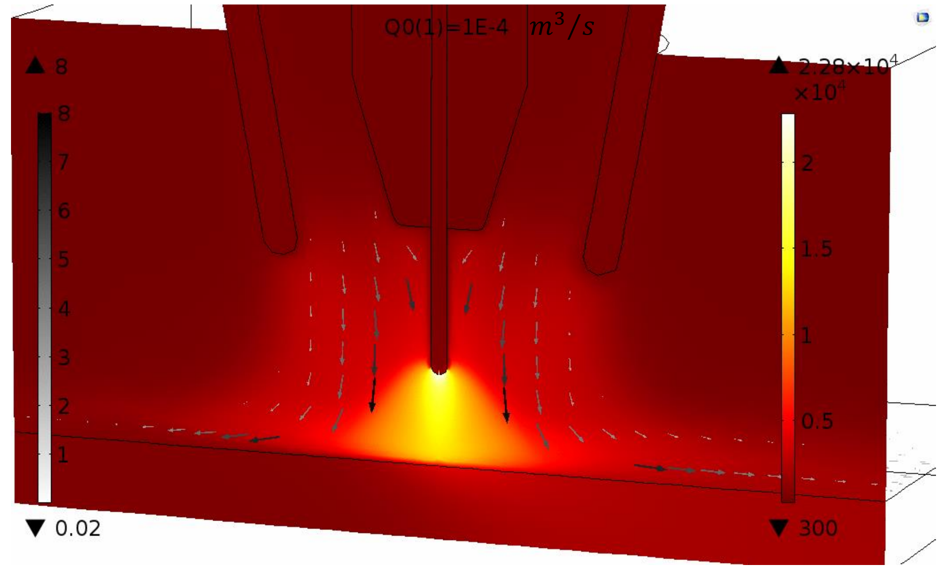
Background: MIG welding process optimisation

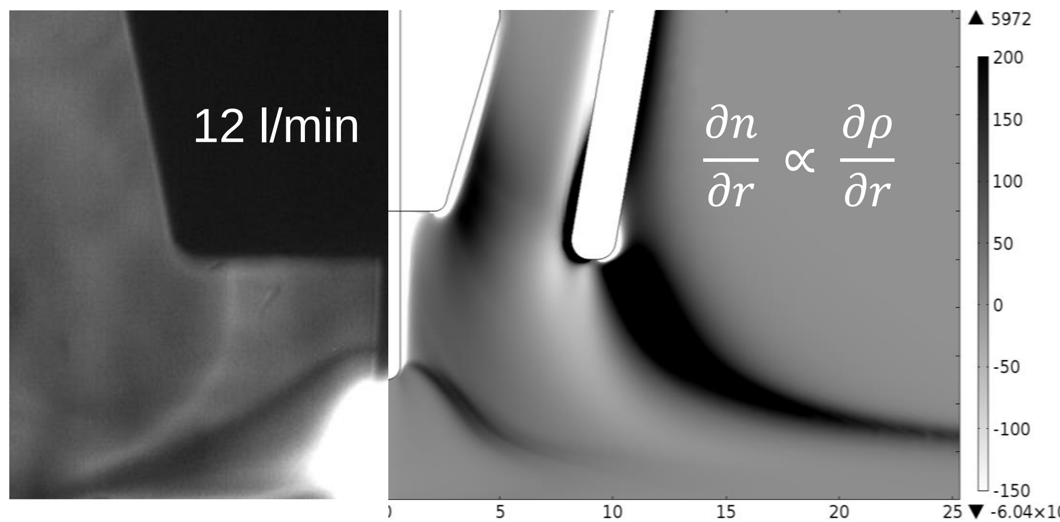




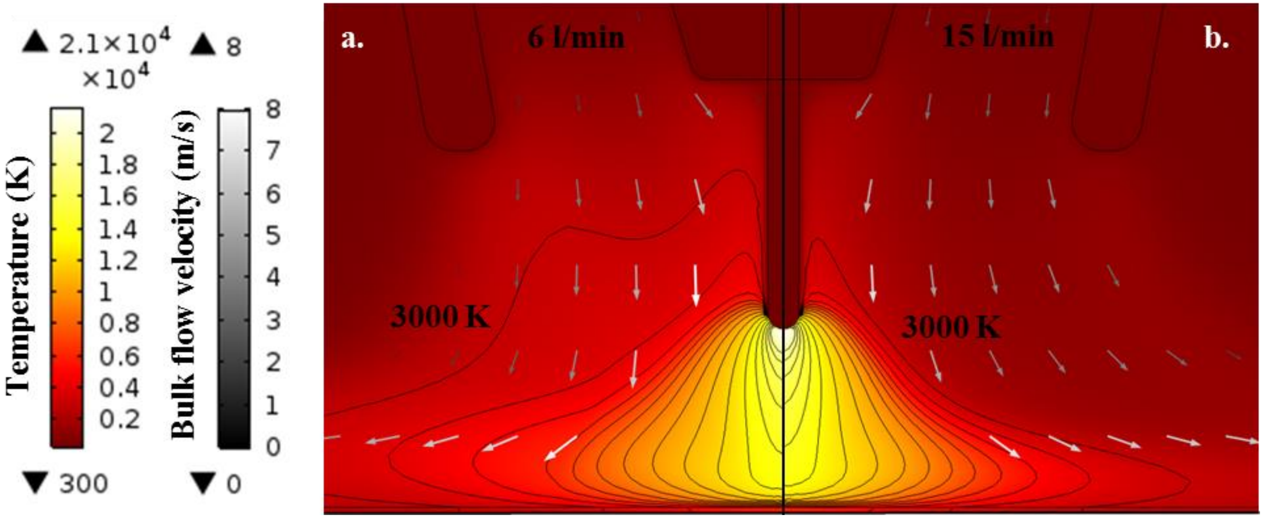
Observed flow features predicted by simulation

Qualitative validation through schlieren





Arc welding simulations

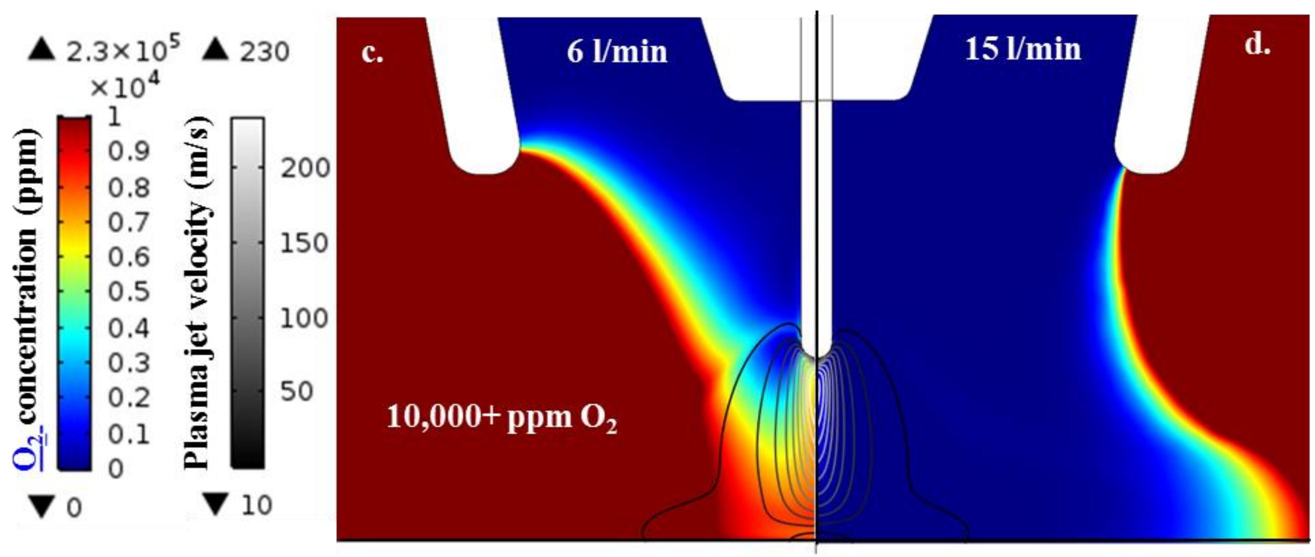


15 l/min nozzle flow constrains jet circa 3000 K isotherm

Arc plasma temperature, velocity similar

Air entrainment more severe at 6 l/min

Availability for air absorption on weld surface



Radiographic cross-examination

6 l/min

9 l/min

Representative films & bead on plate welds

Nozzle standoff (mm)		Ar Flowrate (l/min) 6	9	12	15	Nozzle angle
	10	SW7	SW4	SW1	SW9	0 °
	15	SW8	SW5	SW2	SW10	
	20	X	SW6	SW3	SW11	
	10	SW15	SW14	SW13	SW12	10 °
	10	SW16	SW17	SW18	SW19	20 °
		Porosity	**Acceptable welds**