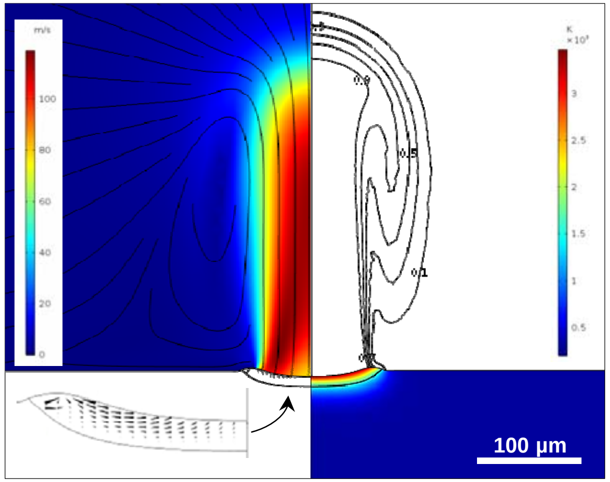
Two-Phase Flow Modelling of Metal Vaporisation under Static Laser Shot using a Double Domain ALE Method

A Feasibility Study

COMSOL CONFERENCE
2018 LAUSANNE



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Summary

1. Background
   → SLM process
   → Potential detrimental role of vaporisation in SLM

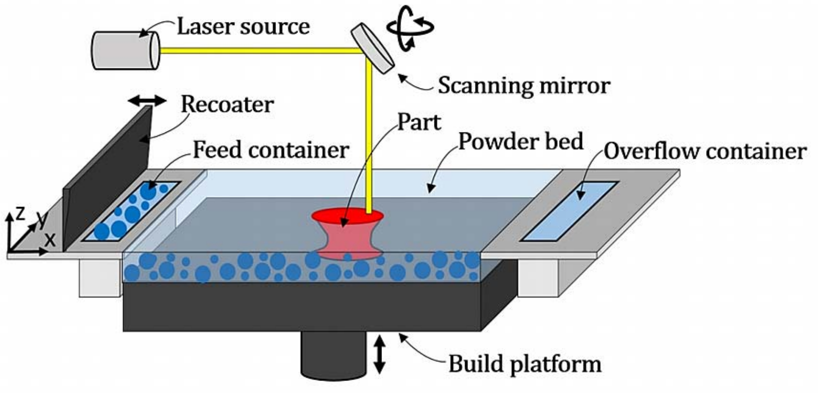
2. Numerical Model
   → Physics
   → Mathematical formulation

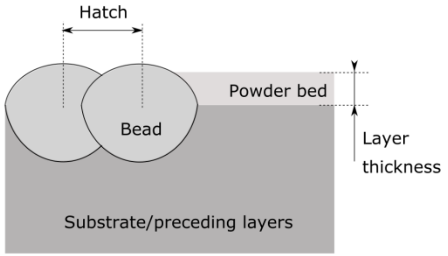
3. Results and Discussion
   → Experimental validation
   → Comparison to analytical model

4. Conclusions and Outlook

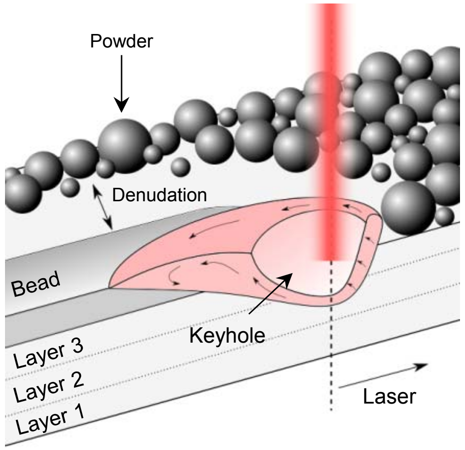
Background

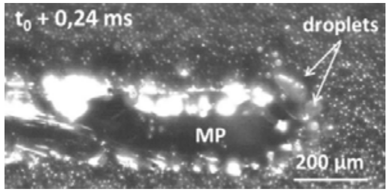
Selective Laser Melting (Additive Manufacturing)



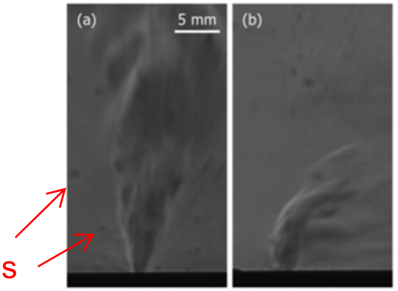


At the local scale, single beads similar to laser welding.





Melt pool surrounded by powder.
[Gunenthiram et al., 2017]



particles

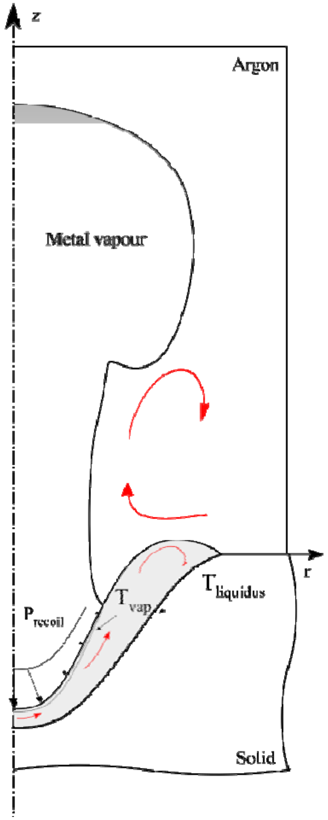
Ejected metal vapour/particles.
[Bidare et al., 2017]

Local phenomena (surface tension, Marangoni, vaporisation), have an impact on the global scale.

NUMERICAL MODEL

What is the Double Domain Approach ?

Here a simplified configuration: 2D axi. without powder bed:



Gas → Set of physics A

- Compressible fluid flow
- Heat Transfer
- Transport of species

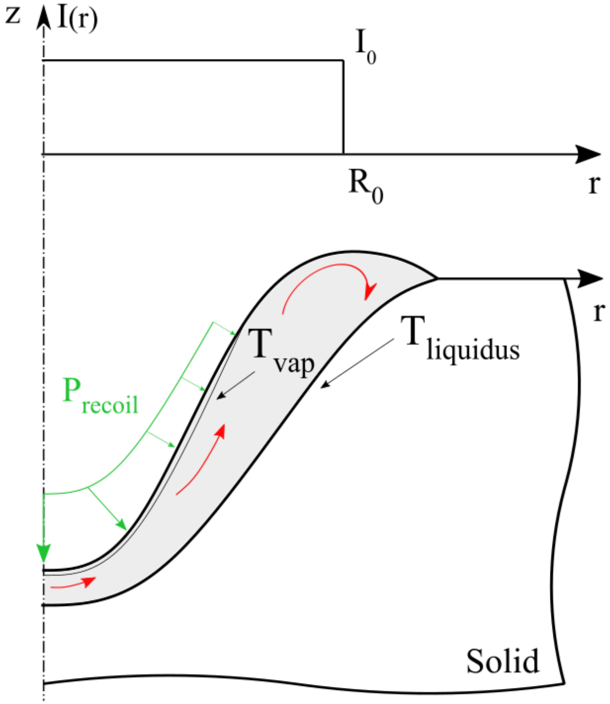
Metal → Set of physics B

- Incompressible fluid flow
- Heat Transfer

Jump conditions
=
Information transfer

- Temperature
- Fluxes
- Stresses
- …

Metal Domain



- Energy conservation:

$$\rho c_p^{eq}\frac{\partial T}{\partial t}+\underbrace{\boxed{\rho c_p\left(\vec{u}\cdot\vec{\nabla}T\right)}}_{\text{convection}}=\underbrace{\boxed{\vec{\nabla}\cdot\left(k\vec{\nabla}T\right)}}_{\text{conduction}}$$

Latent heat of melting

<u>with</u>

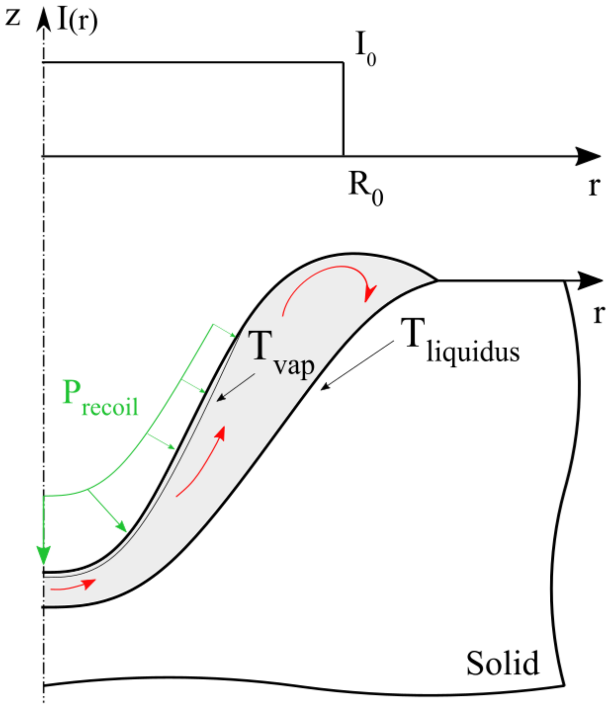
$$c_p^{eq}=c_p+\frac{L_m}{\sqrt{\pi\Delta T^2}}\exp\left[-\frac{(T-T_m)^2}{\Delta T^2}\right]$$

<u>BC</u>

$$\begin{cases} I(r)=A(\theta)cos(\theta)\dfrac{P}{\pi R_0^2}g(t) \quad (r\leq R_0) \\ \underbrace{\boxed{\varphi_{vap}=\dot{m}L_v}}_{\text{vaporisation}} \end{cases}$$

Latent heat of vaporisation

Metal Domain



- Mass conservation:

$$\vec{\nabla} \cdot \vec{u} = 0$$ → Incompressible

- Momentum conservation:

$$\rho \frac{\partial \vec{u}}{\partial t} + \rho(\vec{u} \cdot \vec{\nabla})\vec{u} = \vec{\nabla} \cdot \left\{ -pI + \mu\left[\vec{\nabla}\vec{u} + (\vec{\nabla}\vec{u})^T\right]\right\} + K\vec{u}$$

<u>with</u>

$$K = C_1 \frac{(1 - f_{liq})^2}{f_{liq}^3 + C_2}$$ ⟶ Liquid fraction

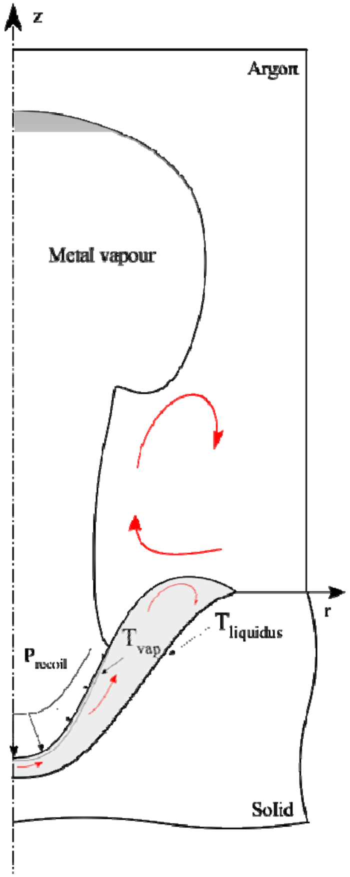
<u>BC</u>

$$\begin{cases} P_{recoil} \propto P_{sat}(T) \\ \vec{f}_\sigma = \sigma\kappa\vec{n} + \vec{\nabla}_S\sigma \end{cases}$$

$P_{recoil} \propto P_{sat}(T)$ ⟶ Clausius-Clapeyron law

$\vec{f}_\sigma = \sigma\kappa\vec{n} + \vec{\nabla}_S\sigma$ Surface tension + Marangoni

Gas Domain



- Energy conservation:

  → Hyp. : temperature continuity

- Mass conservation:

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{u}) = 0$$

→ Compressible

$$\rho = \frac{pM(\omega)}{RT}$$

→ Metal vapour fraction

$$\frac{\partial \omega}{\partial t} + \vec{\nabla} \cdot \left(-D\vec{\nabla}\omega\right) + \vec{u} \cdot \vec{\nabla}\omega = 0$$

(transport of species)

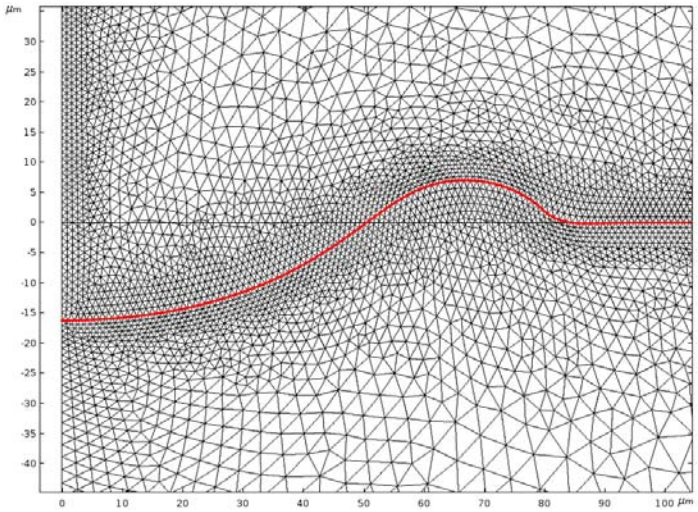
ω = 1 at the interface

- Momentum conservation:

$$\rho \frac{\partial \vec{u}}{\partial t} + \rho(\vec{u} \cdot \vec{\nabla})\vec{u} = \vec{\nabla} \cdot \left\{-pI + \mu\left[\vec{\nabla}\vec{u} + \left(\vec{\nabla}\vec{u}\right)^{T}\right] - \frac{2}{3}(\vec{\nabla} \cdot \vec{u})I\right\} + \rho\vec{g}$$

Interface: ALE + Jump Conditions

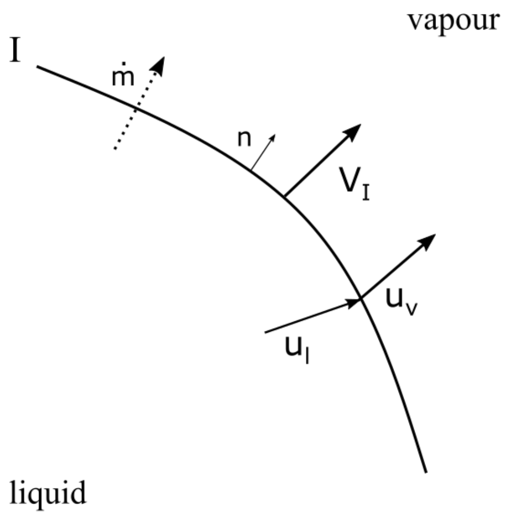
Interface tracking



→ Lagrangian description of the interface.

→ Arbitrary internal nodes motion to optimise mesh deformation.

Jump conditions

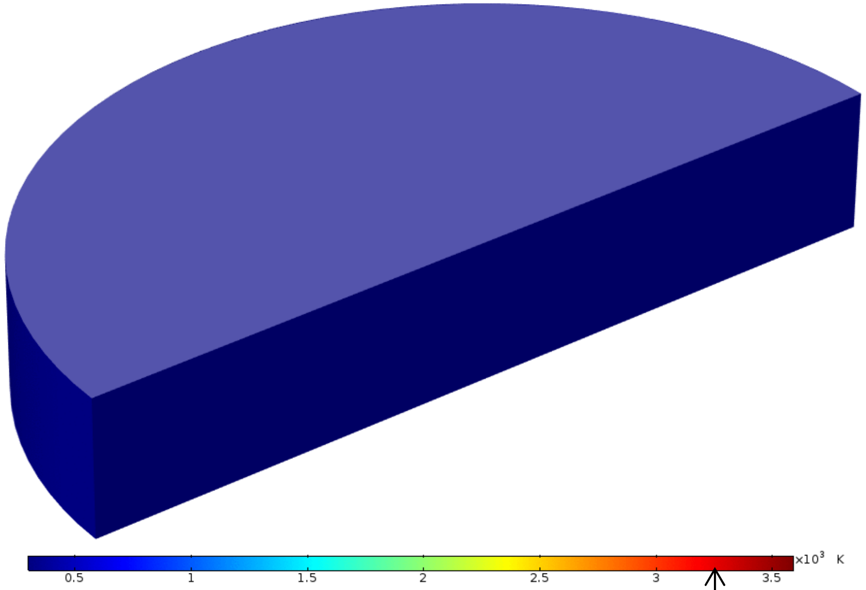


$$\boxed{\rho_v(\overrightarrow{u_v} \cdot \vec{n} - V_I) = \rho_l(\overrightarrow{u_l} \cdot \vec{n} - V_I) = \dot{m}}$$

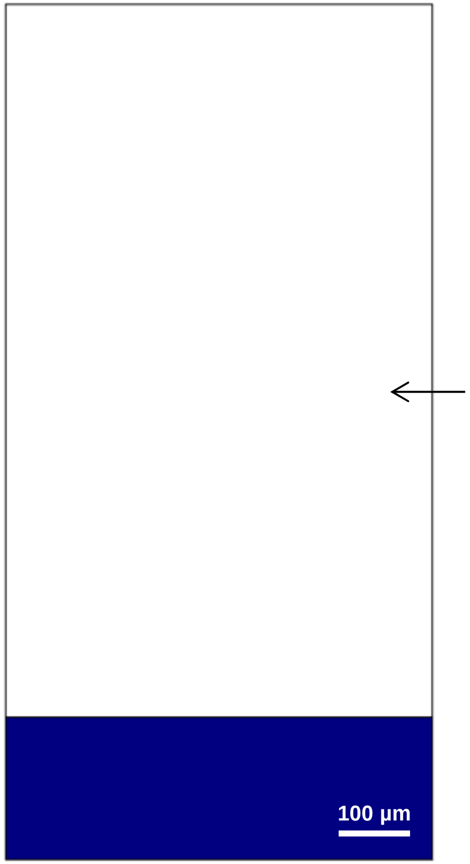
RESULTS AND DISCUSSION

A Few Results

Computation of a 0.3 ms static laser shot



$T_{boiling}$ = 3200 K

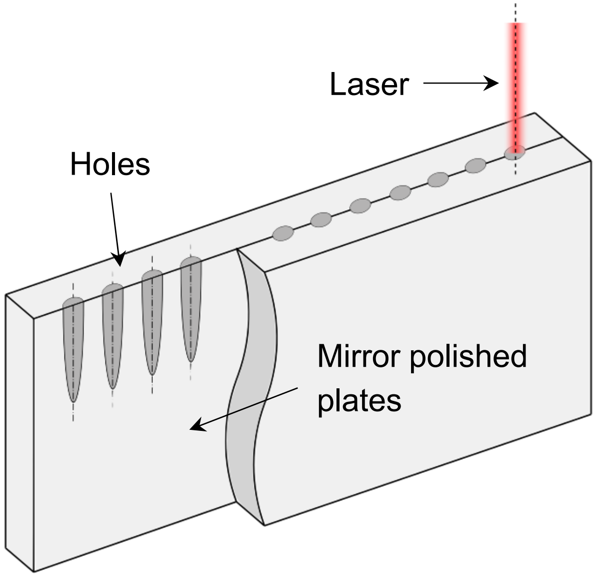


Fraction of metal vapour

Inconel® 625 | P = 400 W | D_0 = 150 µm | $\tau = 0.3\text{ms}$

Minimum Requirement: Dimensions of the Melted Zones

- Experimental configuration:

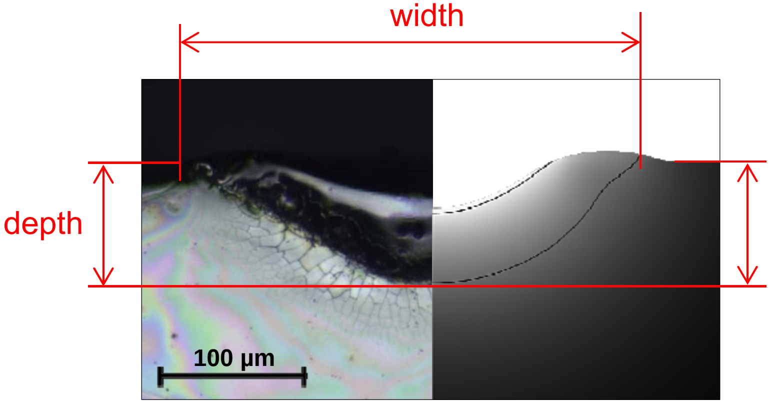


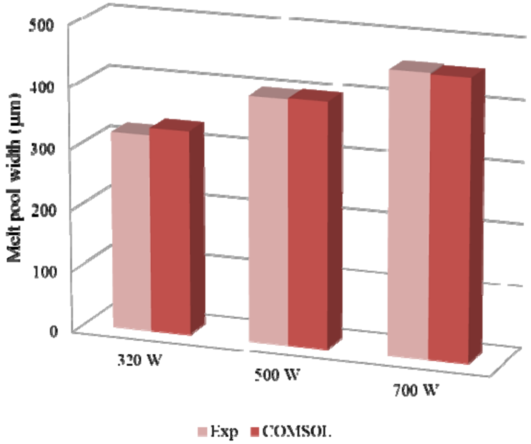
Direct Observation of Drilled hOles (DODO) method
[Schneider et al., 2010].

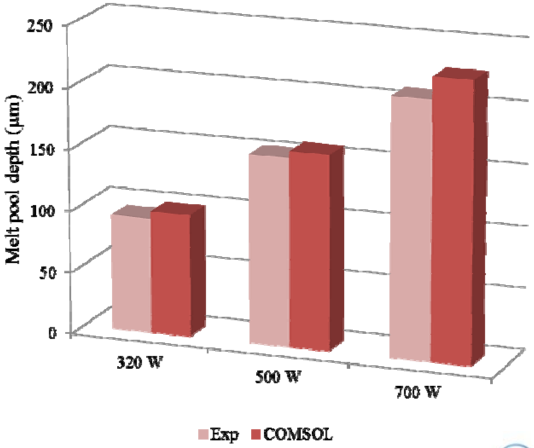
P [W]	D_0 [µm]	τ_{pulse} [ms]
320 - 500 - 700	**205 (top hat)**	**3**

Material: Inconel® 625

Dimensions of the Melted Zones





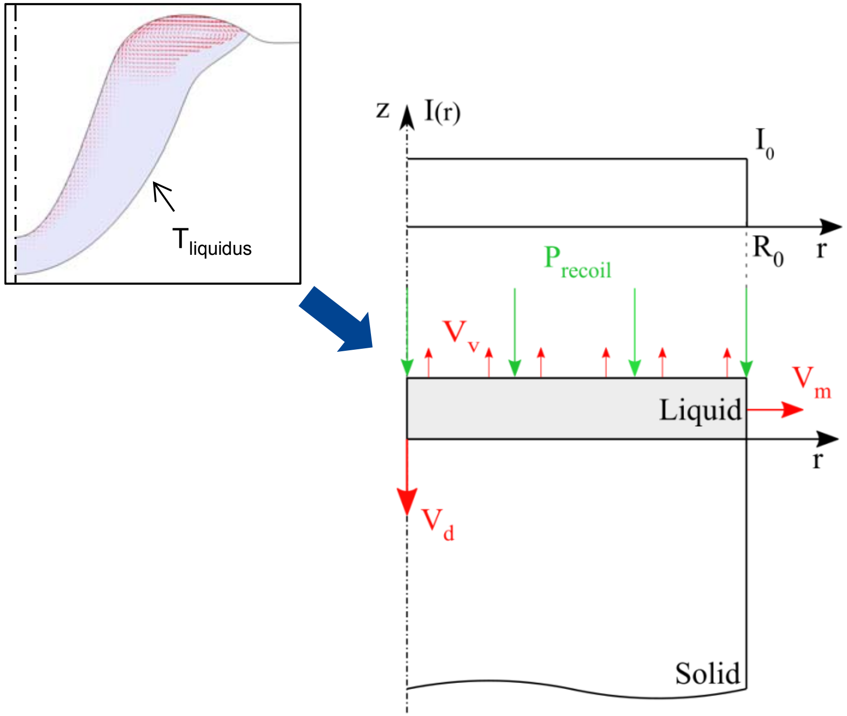


- Shape of the melt pool well described
- Melt pool width estimated within a range of ± 5%
- Melt pool depth overestimated by about 7%

→ Promising results

Heat Transfer in the Melted Zone

- Comparison to the “piston model” (analytics)



- Mass balance

$$(\text{Solid})_{\text{in}} = (\text{Liquid} + \text{Vapour})_{\text{out}}$$

- Energy Balance (stationary state)

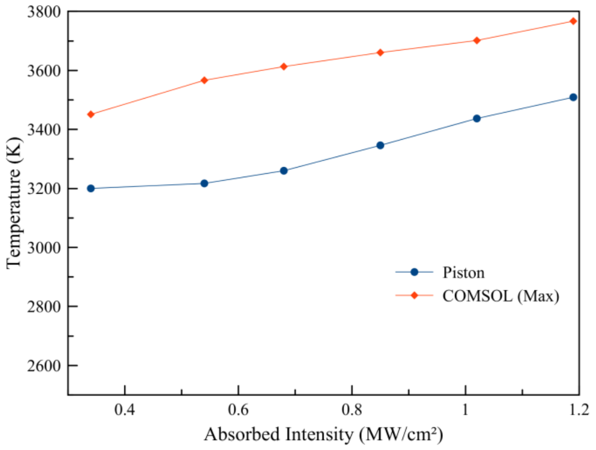
$$P_{\text{laser}} = \mathrm{P}_{\text{conduction}} + \mathrm{P}_{\text{convection}} + \mathrm{P}_{\text{vaporisation}}$$

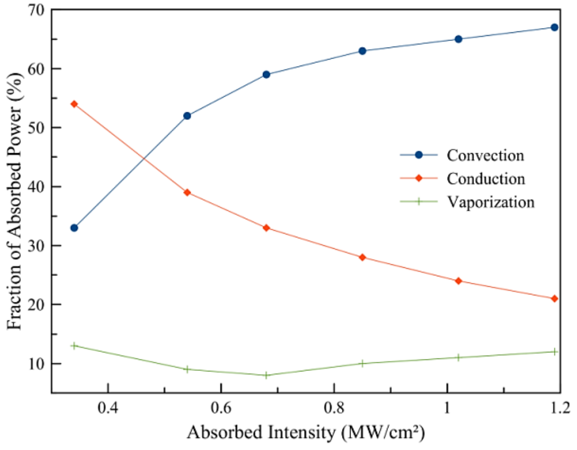
Hyp: Flat surface, homogeneous surface temperature, non-viscous fluid.

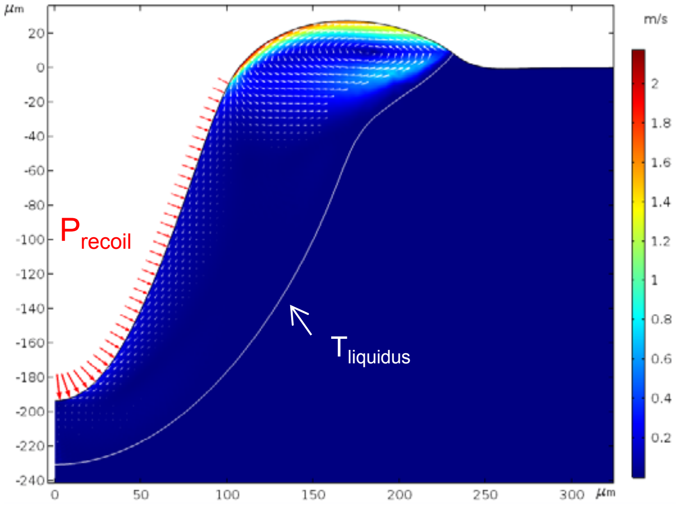
Links I_{laser} to :

→ Interface average temperature.
→ Drilling velocity.
→ Heat exchange.

Heat Transfer in the Melted Zone







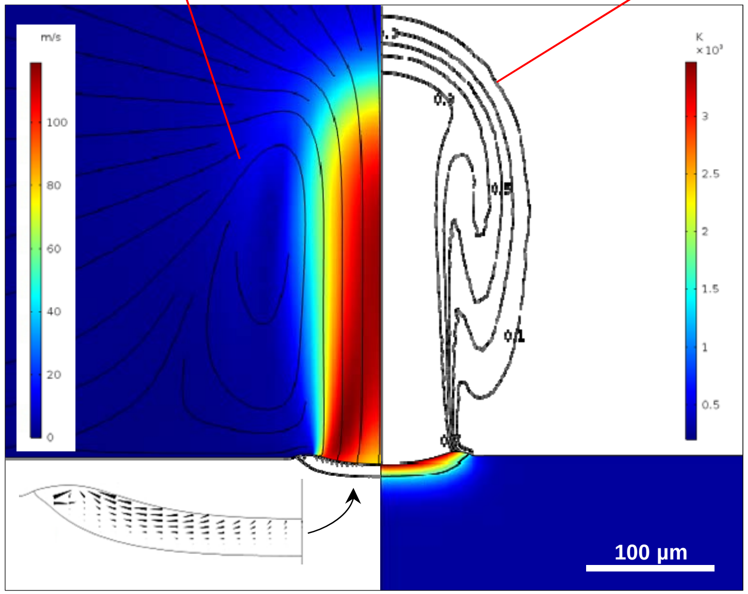
P = 700 W | D_0 = 205 µm | $\tau = 3\text{ms}$

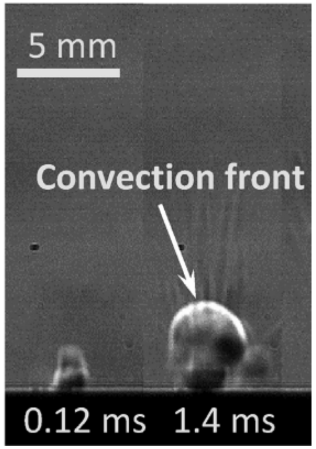
- Temperatures predicted follow the same trends (+10% for the numerical model).
- Melt pool convection is the dominant heat exchange mechanism.
- Recoil pressure drives the melt flow.

Vapour Flow

Recirculation flow reported to cause denudation.

Mushroom shape: Rayleigh-Taylor Instability.





[Bidare et al., 2017]

- High velocity of the vapour plume (> 100 m/s).

→ In agreement with most studies in the literature.

CONCLUSIONS AND OUTLOOK

Conclusions

- *Promising approach*

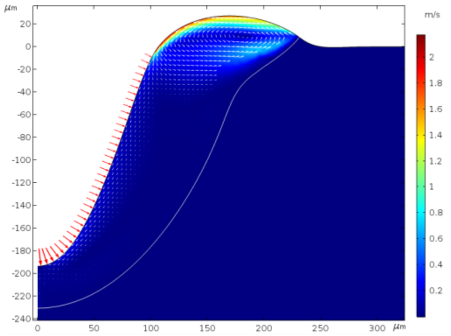
→ *Highly multi-physical.*

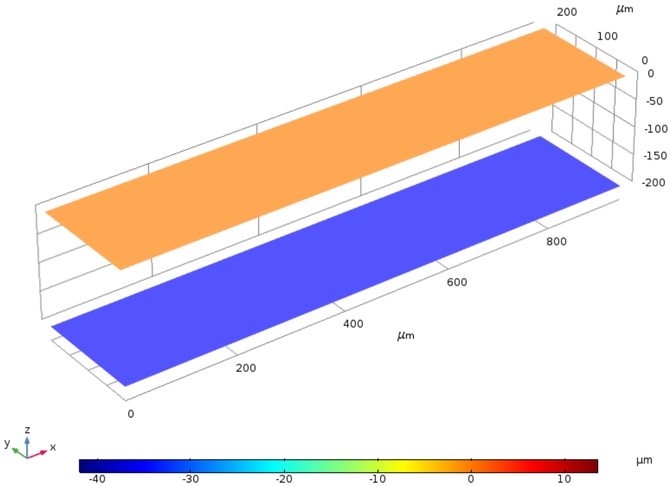
→ *Reproduces the 2D axi. shape of the melt pool.*
→ *Predicts the melt pool dimensions with accuracy.*
→ *Melt pool temperature trends and orders of magnitude in agreement with the "piston" model.*

→ *Good orders of magnitude of the vapour plume velocity.*
→ *Mushroom structure of the vapour plume.*
→ *Recirculation flow on the side of the vapour plume.*

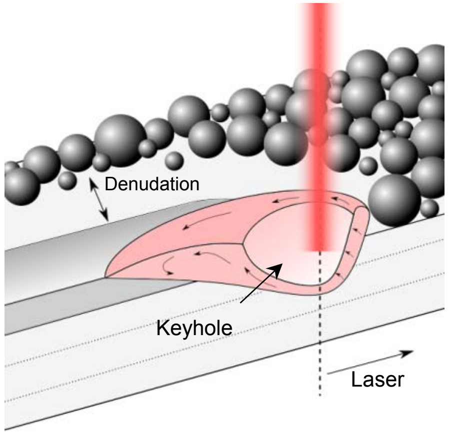
- *Future work: need more experimental validation.*

Outlook: 3D configuration ?





P = 300 W | D_0 = 80 µm | V = 0.8 m/s



2D axisymmetric (drilling)

3D (welding)

3D + Powder (SLM)

THANK YOU FOR YOUR ATTENTION

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