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Spatio-temporal characterization of gaseous layer development during plasma electrolytic polishing

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FROM IDEA TO PROTOTYPE

Outline

1. Introduction
    - What is plasma electrolytic polishing (PEP)?
    - Application of PEP
    - Principle of PEP

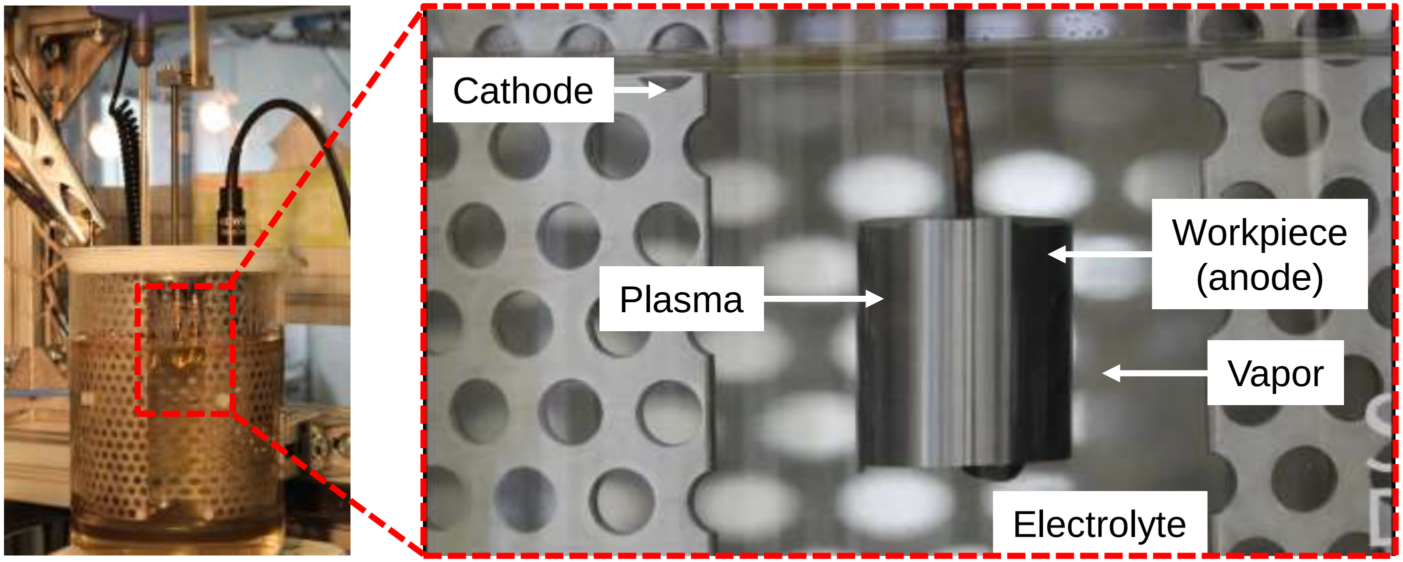
2. Experimental details

3. Results and discussion
    - Electrical current and workpiece temperature
    - ~~Electrical current and high-speed camera (bubble behaviour)~~
    - Evaluation of transfered power towards the substrate
    - Modelling of electrolyte temperature

4. Summary

Introduction

Plasma electrolytic polishing (PEP)



Advantages of Plasma Electrolytic Polishing (PEP)

- ✓ Enables to treat complex-shaped samples
- ✓ Usage of environmentally-friendly electrolyte (> 90% water)
- ✓ Various surface modifications

  e.g. smoothing, degreasing, deburring, and oxidizing …

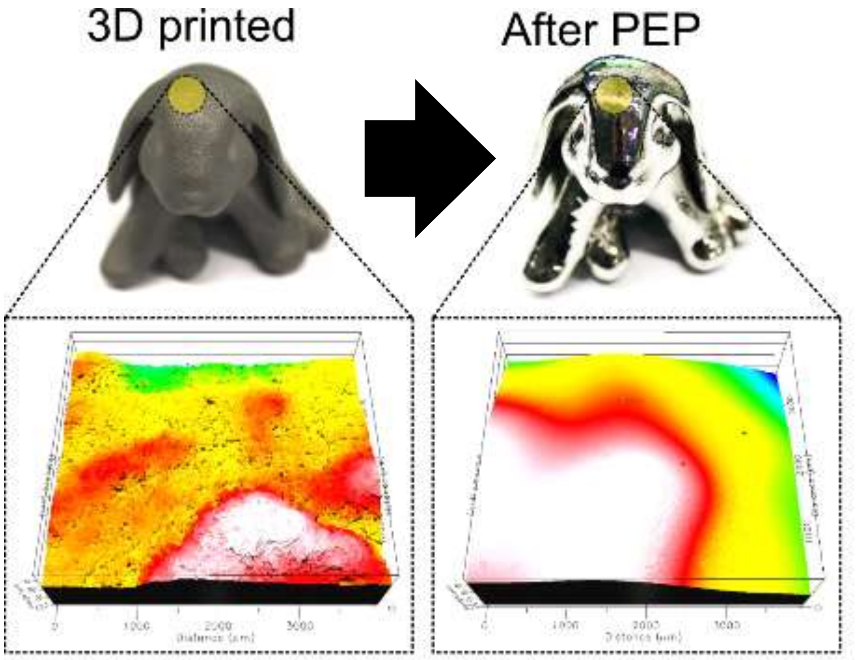
Introduction

Application of PEP

S. An et al., Surf. Coat. Tech. 405 (2021) 126504

Surface polishing effect

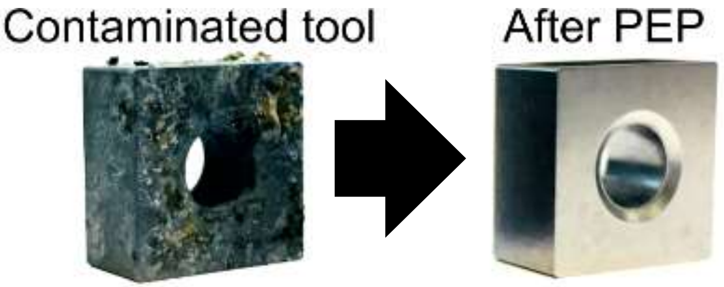
on stainless steels

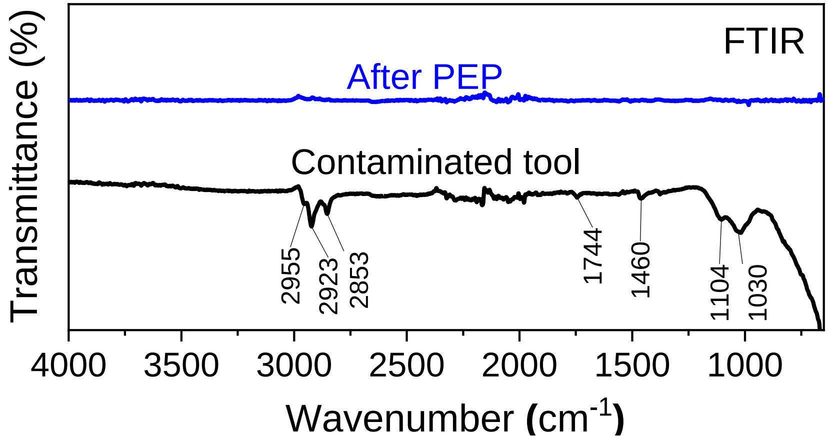


3D surface profile by white light interferometer (WLI)

Surface cleaning effect

on WC-Co

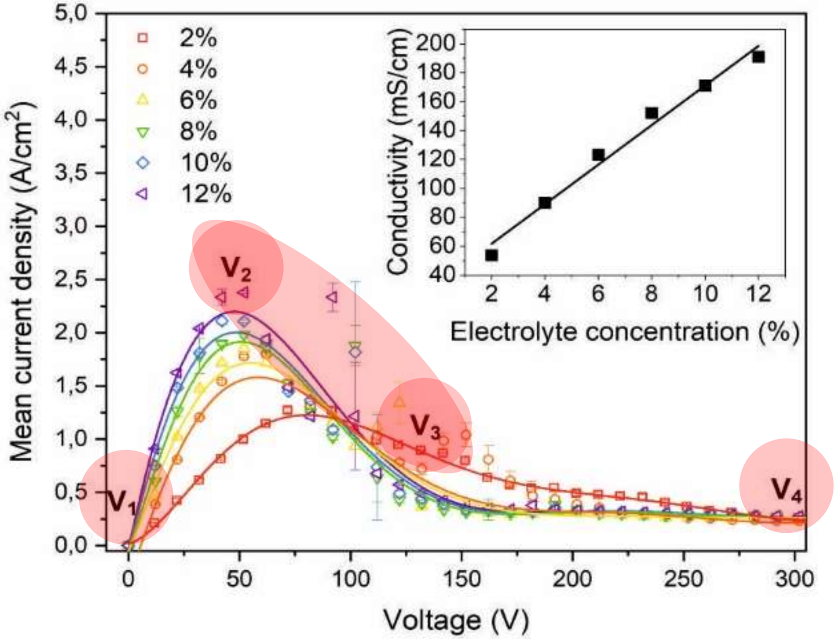


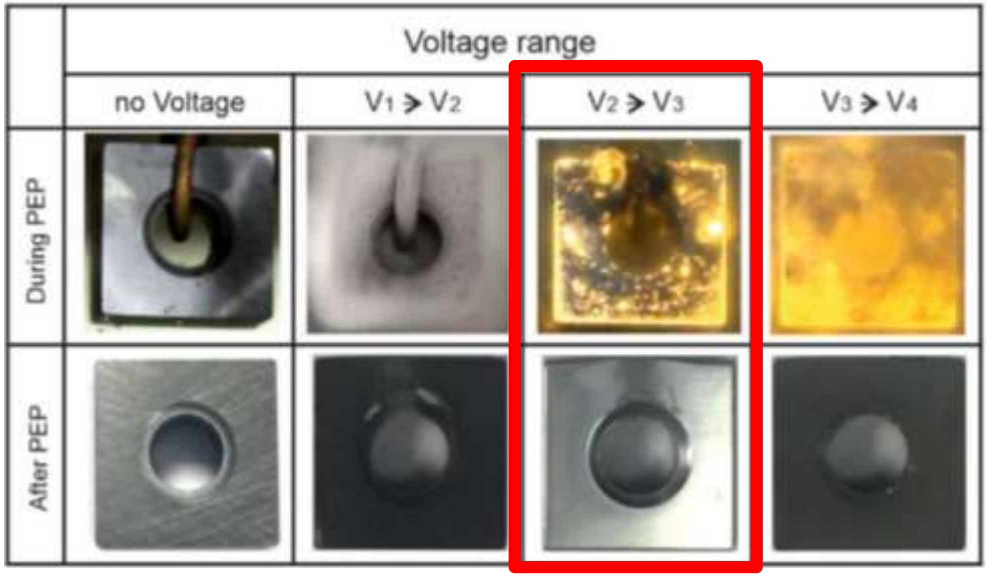


- Surface roughness (R_a) was reduced from 1.9 to 0.1 µm
- Surface contaminants were removed after the PEP process

Introduction

I-V characteristics of PEP



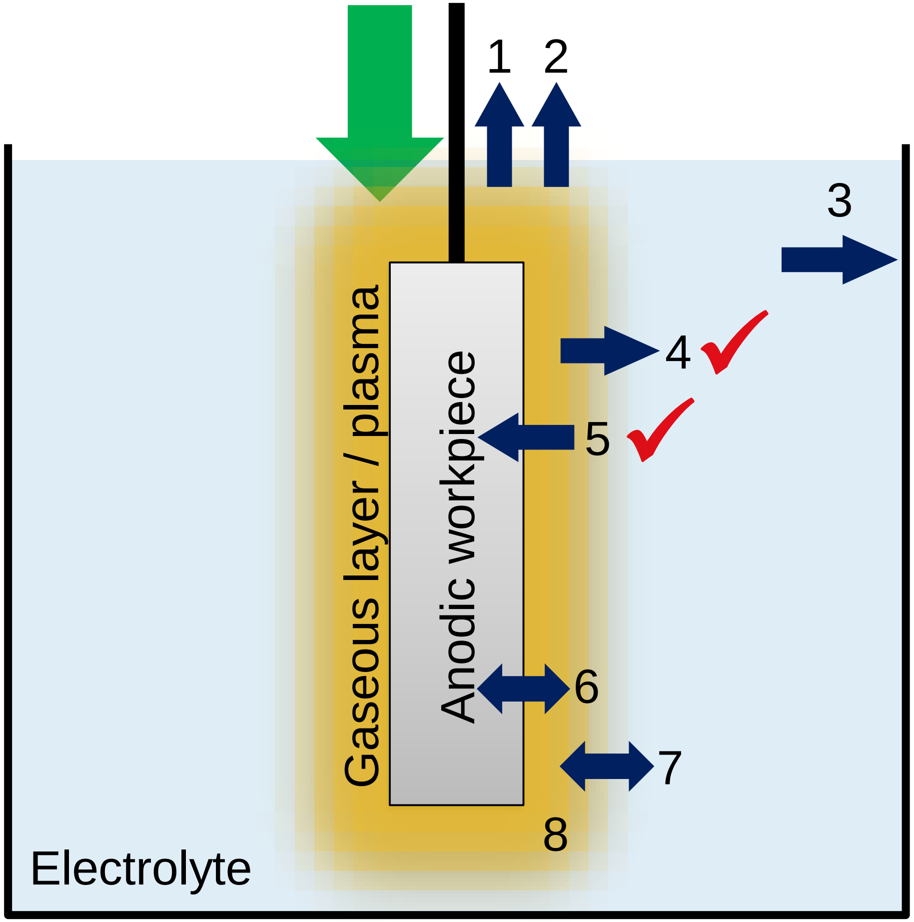


S. An et al., Surf. Coat. Tech. 405 (2021) 126504

- Current density starts to decrease at the voltage regime $V_2 \rightarrow V_3$ due to the appearance of vapor layer around the workpiece
- Material dissolution reaction is dominant rather than surface oxidation in this regime
- The stability of the gaseous layer directly influences the material removal rate and homogeneity

Introduction

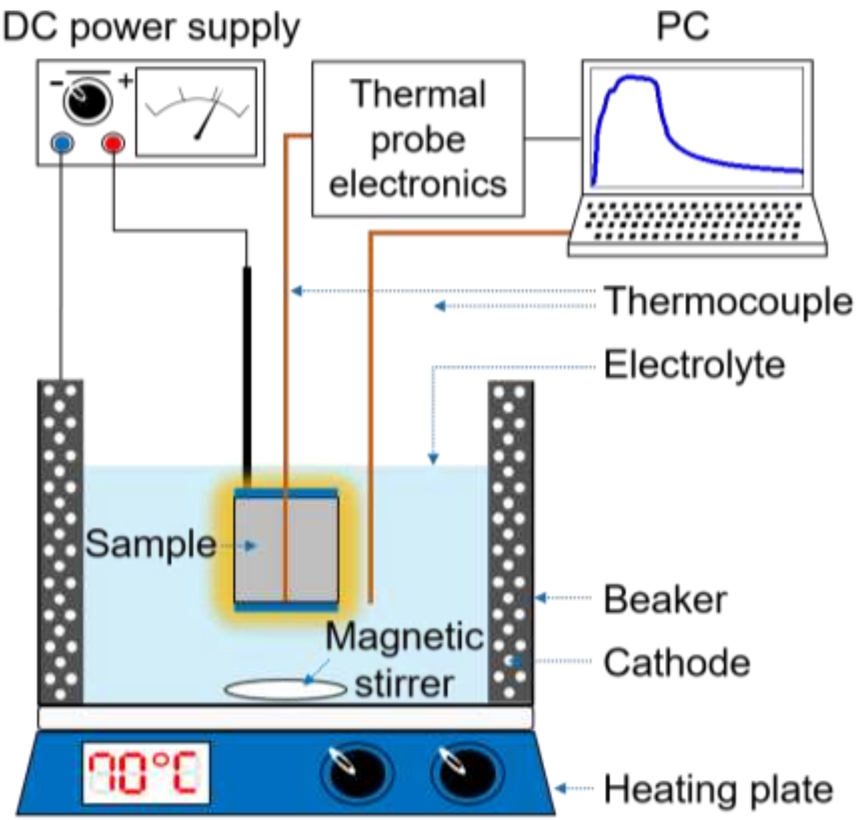
PEP: Energy transfer aspect



- **Input**
  Electrical energy

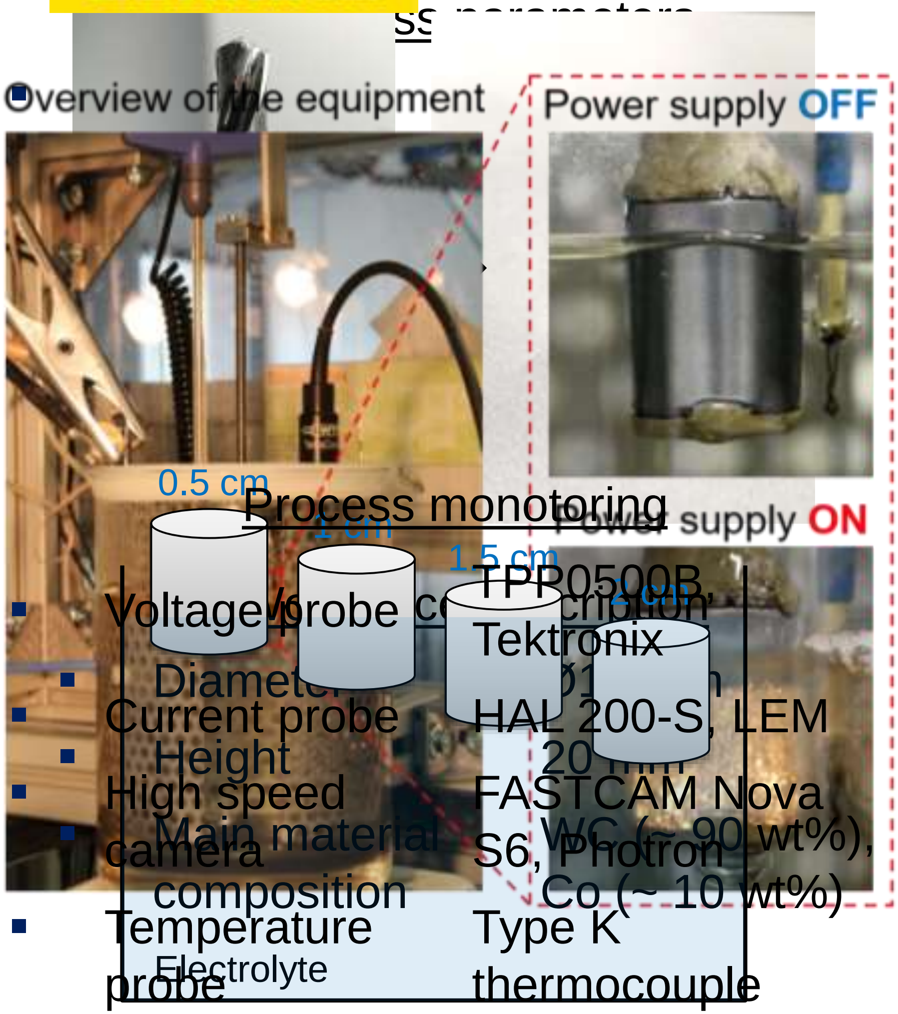
- **Output**
  1. Heating of the air
  2. Evaporation
  3. Heating of the vessel
  4. Heating of the electrolyte
  5. Heating of the workpiece
  6. Chemical reactions at the workpiece surface
  7. Electrochemical reactions between electrolyte and gaseous layer/plasma
  8. Sustaining of plasma

Experimental details



Schematic illustration of PEP experimental setup

GÜHRING Cemented carbide



Process monotoring

Voltage probe	TPP0500B, Tektronix
Current probe	HAL 200-S, LEM
High speed camera	FASTCAM Nova S6, Photron
Temperature probe	Type K thermocouple

ss parameters

	Description
Diameter	Ø1 m
Height	20 mm
Main material composition	WC (~ 90 wt%), Co (~ 10 wt%)

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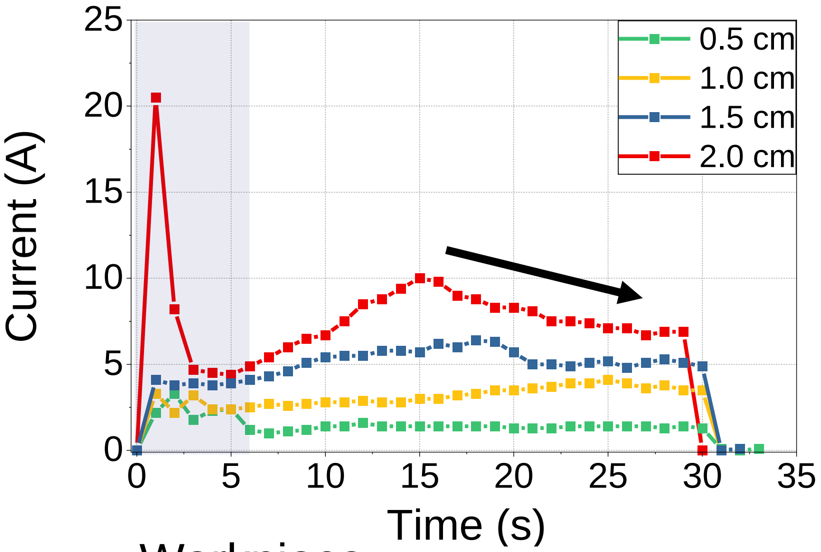
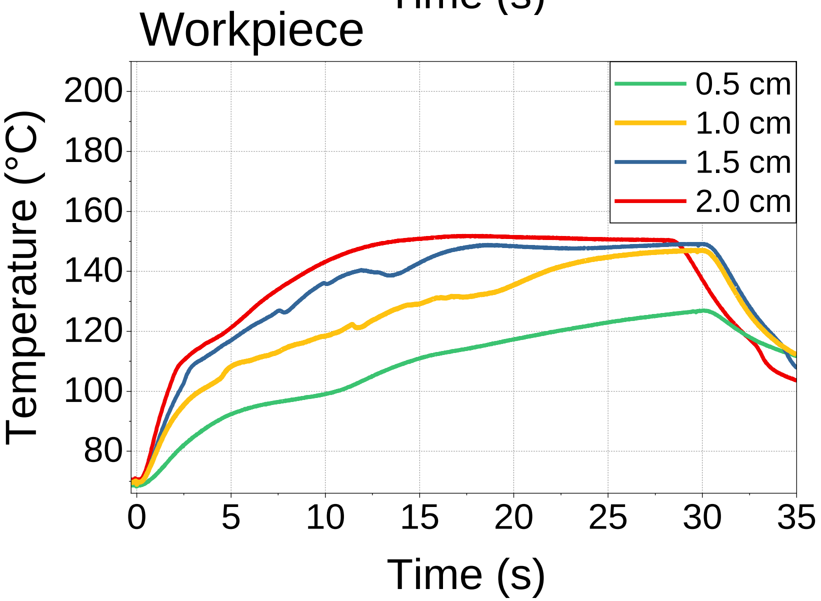
    - Modelling of electrolyte temperature
4. Summary

Results and discussion

Electrical current and temperature measurement



- **Electrical current** rises as the immersion depth (d) increases (area ↑)
- Initially, the hydrodynamic instability of the gas layer induces an unstable flow of current
- The stabilized gaseous layer lowers current flow



- The maximum **workpiece temperatures** reach ~ 150 °C (except for 0.5 cm)
- Lowering the immersion depth (d) extends the time needed to achieve equilibrium temperature
  - ➔ Less power supplied, hence less power for heating
  - ➔ Convective cooling by the air?

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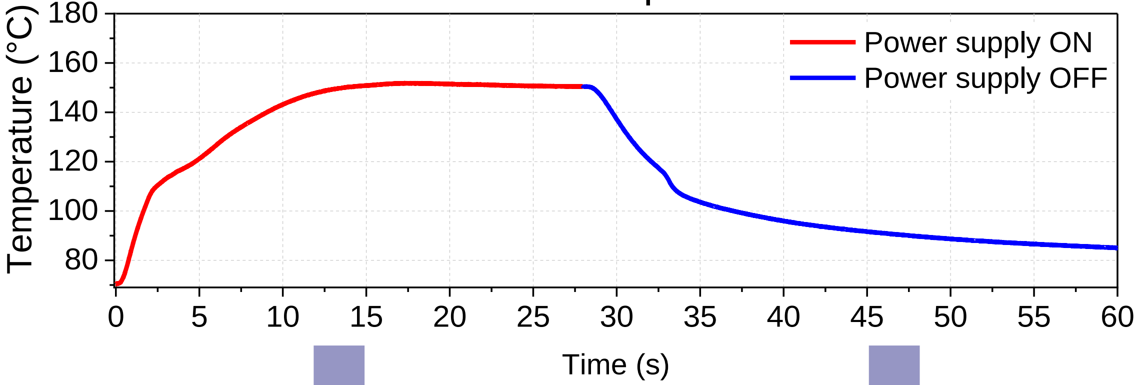
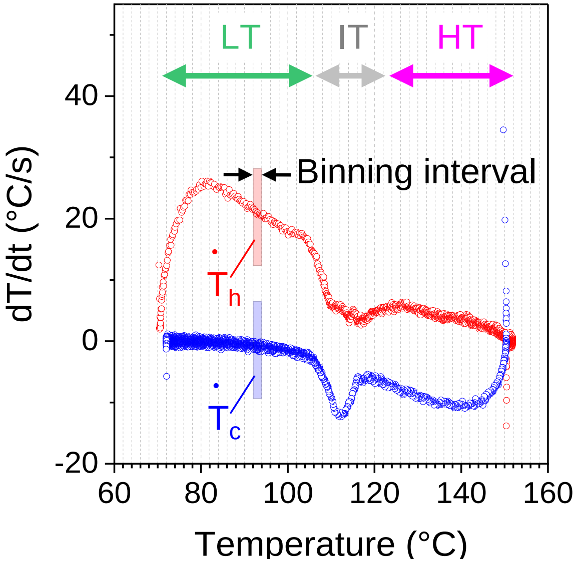
Results and discussion

Thermal probe - Evaluation of the power transferred to the workpiece

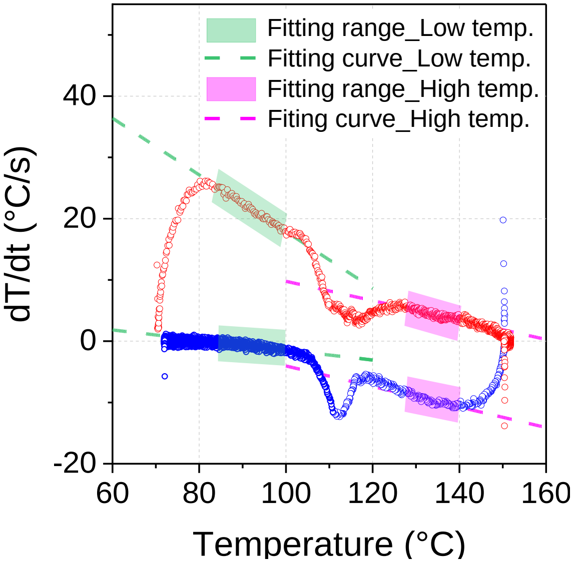
Measured temperature



Binning method



Interpolation method



heating (power supply on)

$$\dot{H}_h = C_s\dot{T}_h = P_{in} - P_{out,h}$$

cooling (power supply off)

$$\dot{H}_c = C_s\dot{T}_c = -P'_{out,c}$$

Simplifying assumption:

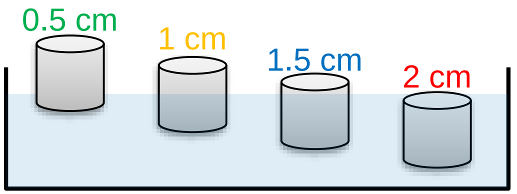
$$P_{out,h} = P'_{out,c}$$

leads to: $P_{in} = C_s\left(\dot{T}_h - \dot{T}_c\right)$

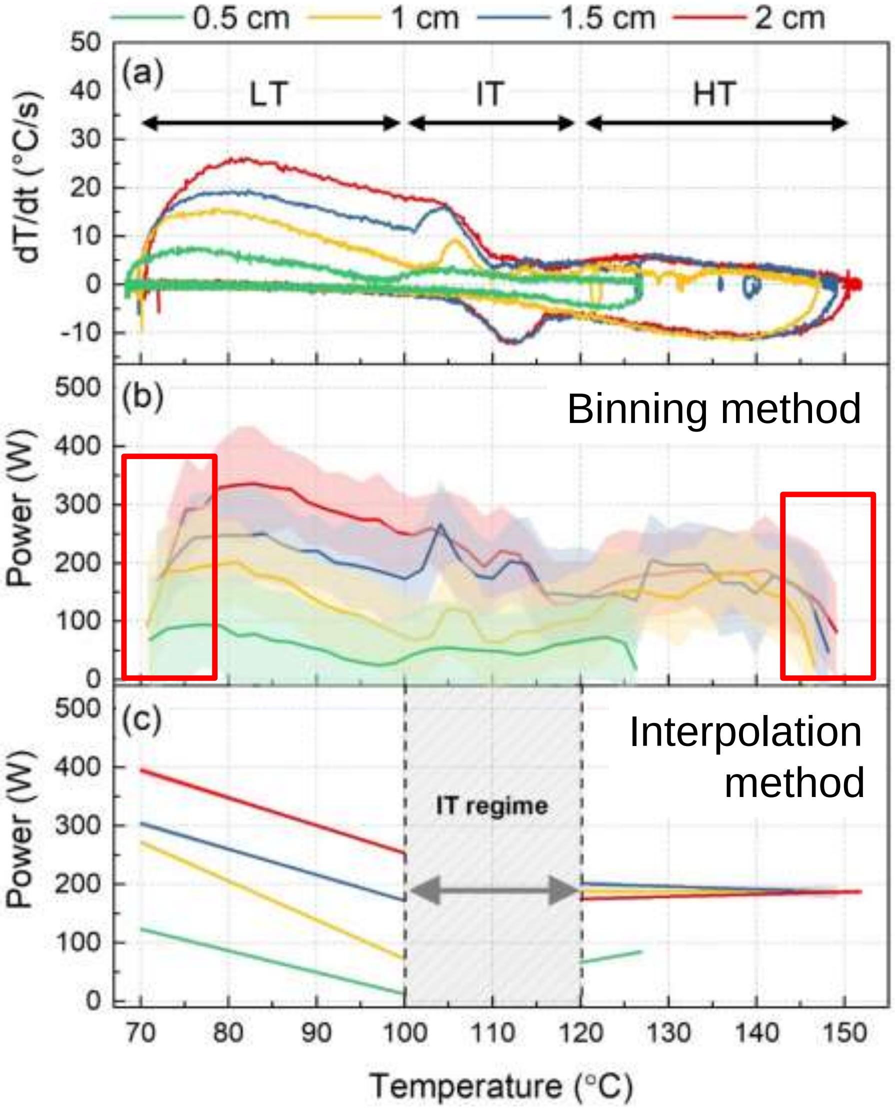
$\dot{\mathbf{H}}$: Time derivative substrate enthalpy
$\dot{\mathbf{T}}$: Time derivative of the substrate temperature
$\mathbf{C_s}$: Substrate heat capacity
$\mathbf{P_{in}}$:Power transferred to the substrate
$\mathbf{P_{out}}$: Power losses from the substrate

[1] Hansen et al., Understanding the energy balance of a surface barrier discharge for various molecular gases by a multi-diagnostic approach, 129 (2021) 053308.

Results and discussion



Evaluation of the power transferred to the workpiece



Time derivative of temperature

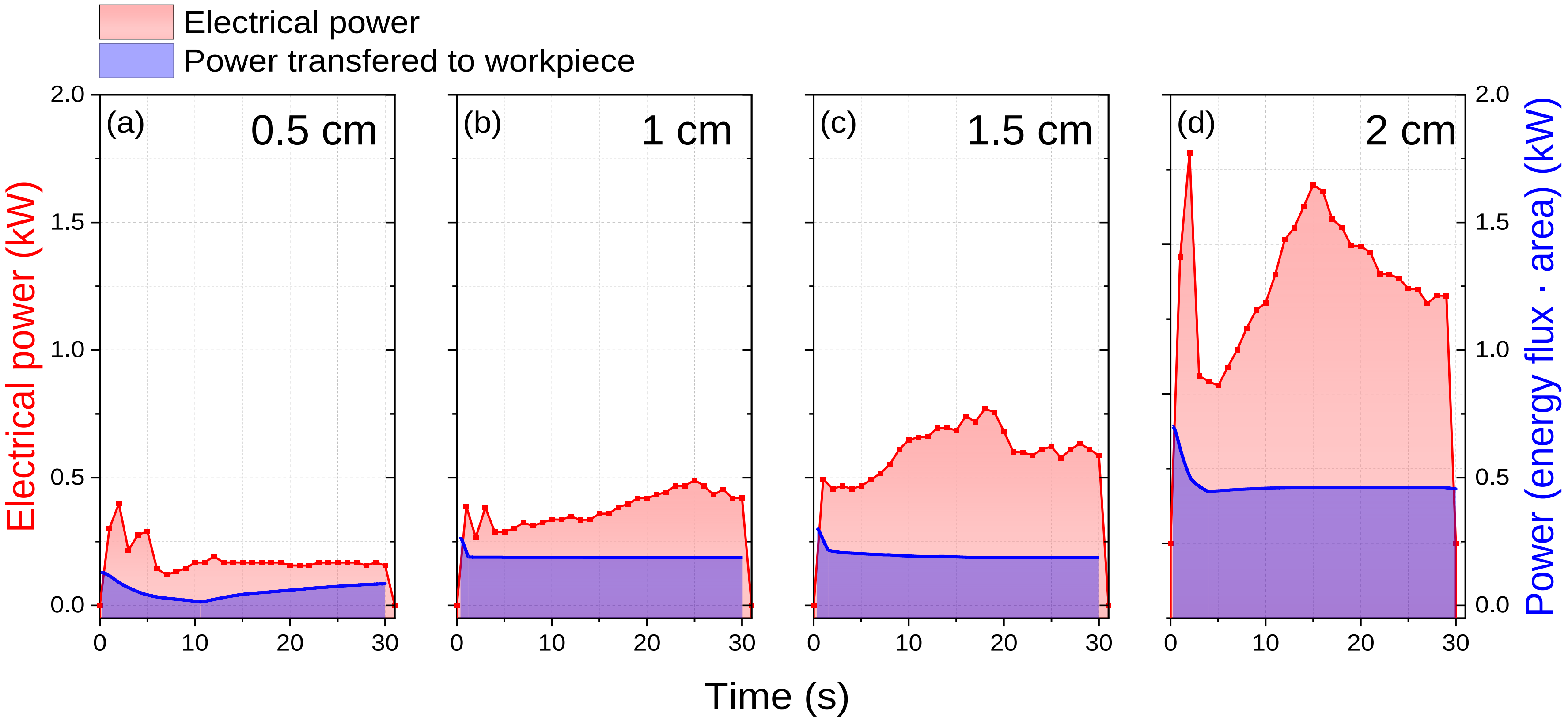
- Distinct heating phases observed at varied immersion depths
- For d = 0.5 cm the obtained data is less reliable due to less heating and incomplete gaseous layer

Power transferred to the workpiece

- LT regime
  P_{in} depends on the immersion depth of the workpiece
- HT regime
  P_{in} becomes independent of the depth (converging curves ≥ 120 °C)
- Gaseous layer inhibits heat transfer to electrolyte

Results and discussion

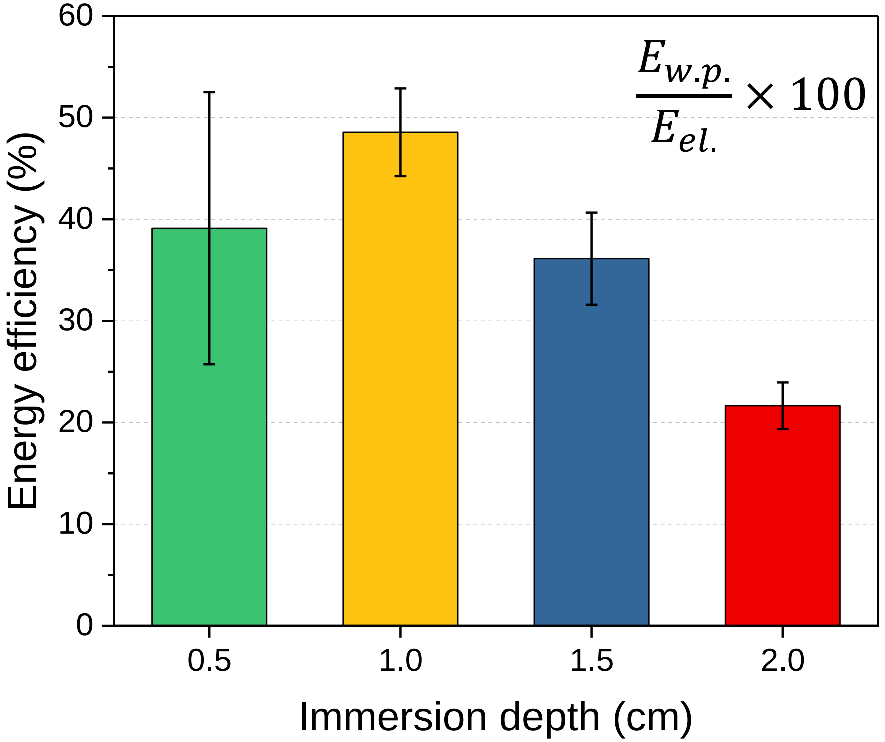
Power efficiency

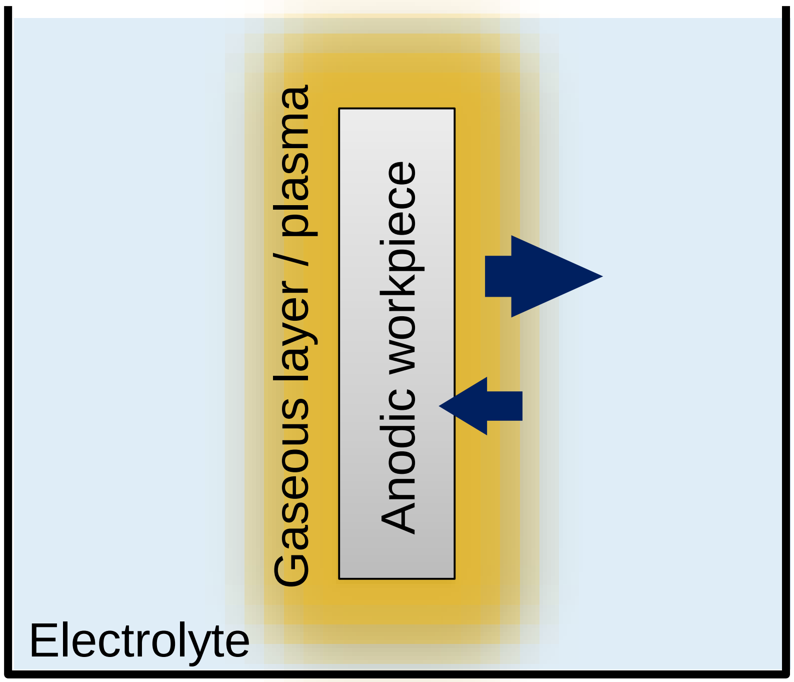


- Less energy is transferred to the workpiece when stabilized gas layer has developed (~ 4 s in the case of d = 2 cm)
- As the immersion depth increases, the proportion of the power transferred to the workpiece decreases presumably due to more power transfer to electrolyte

Results and discussion

Energy efficiency

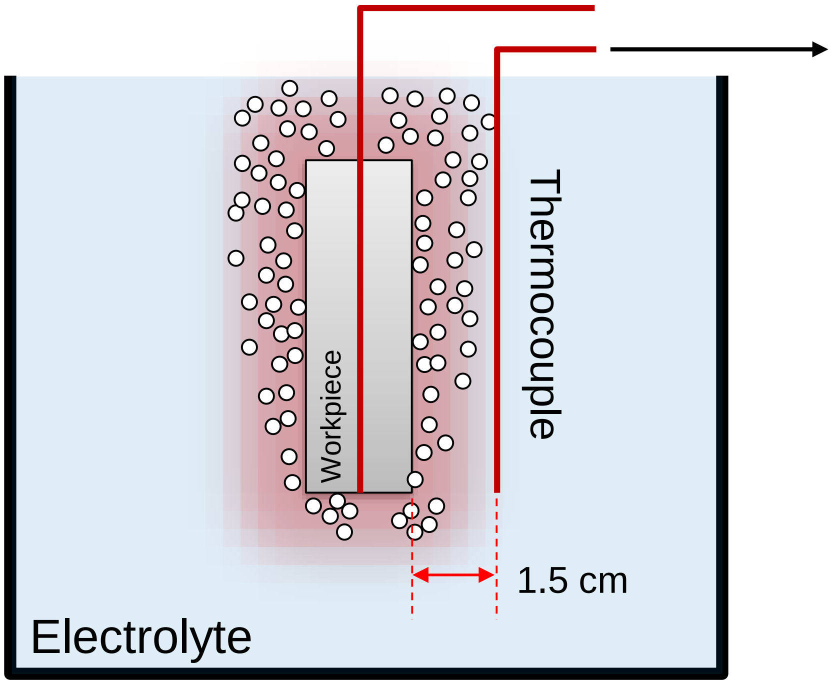


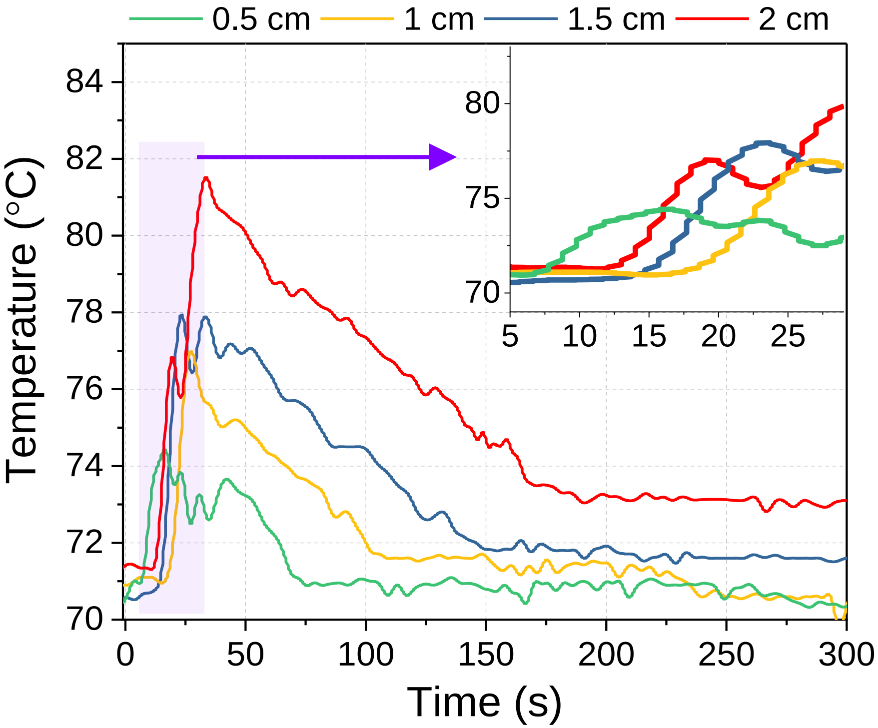


- The fraction of energy transferred from the input electrical energy to the anodic workpiece reduces from 39% to 21%
- In the case of d = 0.5, the value is underestimated due to insufficient treatment time
- As immersion depth increases, more energy consumed to heat the surrounding electrolyte

Results and discussion

Electrolyte temperature





- The temperature increment is higher when the immersion depth is deeper since more electrical power is consumed with larger exposed workpiece area
- The lowering of immersion depth from 2 to 1 cm causes a deceleration in the rise of electrolyte temperature.

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   - **Modelling of electrolyte temperature**

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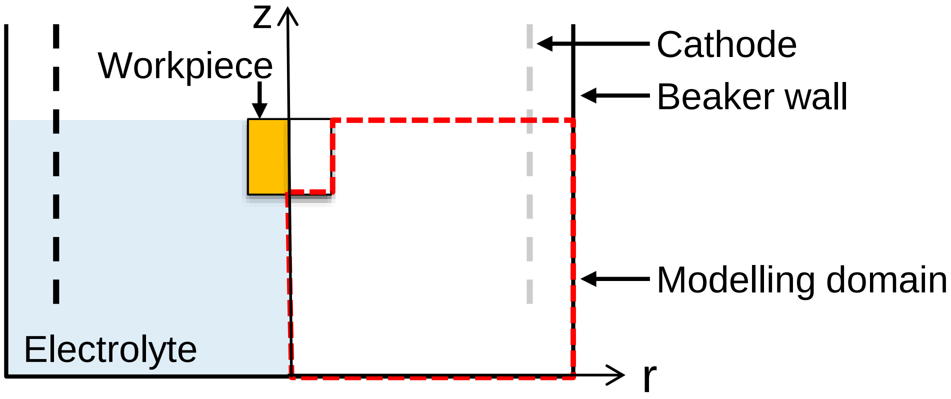
Results and discussion

Modelling of electrolyte temperature

Sketch of the modelling domain



- 2D time-dependent model in cylindrical geometry
- Equations are solved in COMSOL software by finite element numerical method
- Starting conditions: 70 ºC at anode, simulating for 30 s of process duration

$\vec{u}$	flow velocity field	ρ_f	density of fluid	T	Temperature
ρ	density of mixure (gas and fluid)	Φ_g	volume fraction of gas	H_{gf}	latent heat
p	pressure	D_{md}	turbulent dispersion coefficient	$\vec{q}$	conductive heat flux
I	unit tensor	c_p	heat capacity	ρ_g	density of gas
K	viscous stress tensor	m_{gf}	mass transfer between gas and fluid		

Mixture flow model (turbulent k-ε)

Conservation of momentum

$$\rho\frac{\partial\vec{u}}{\partial t}+\rho\cdot(\vec{u}\cdot\nabla)\vec{u}=\nabla[p\boldsymbol{I}+\boldsymbol{K}]+\rho\vec{g}$$

Conservation of mass (continuity equation)

$$\nabla\vec{u}=m_{gf}\left(\frac{1}{\rho_g}-\frac{1}{\rho_f}\right)$$

Transport of gas phase

$$\frac{\partial\Phi_g}{\partial t}+\vec{u}\cdot\nabla\Phi_g=\nabla\left(D_{md}\nabla\Phi_g\right)-m_{gf}\frac{\rho}{\rho_g\rho_f}$$

Heat transfer model

Heat transfer in fluid

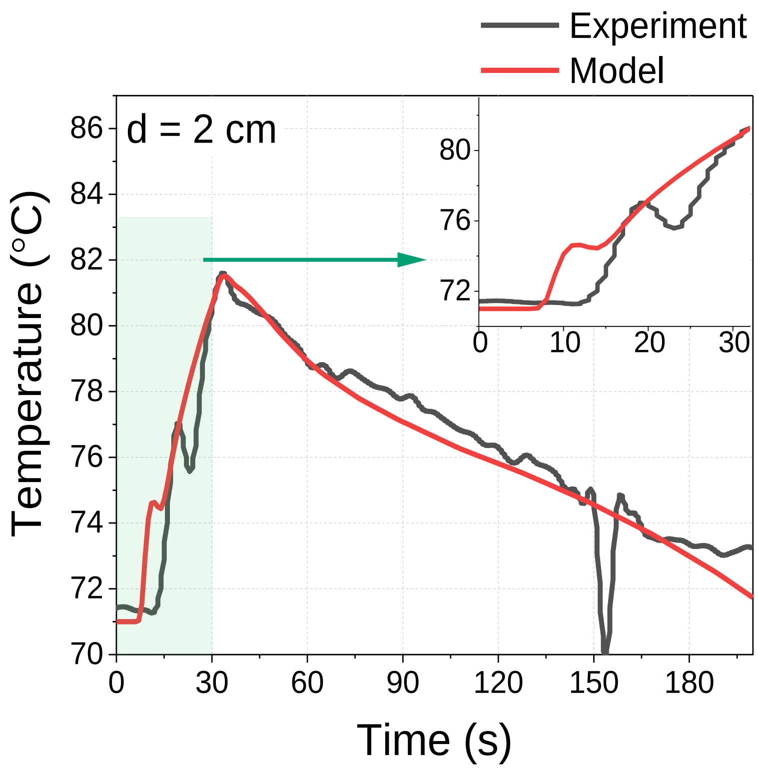
$$\rho c_p\frac{\partial T}{\partial t}+\rho c_p\vec{u}\cdot\nabla\mathrm{T}+\nabla\vec{q}=-m_{gf}\Delta H_{gf}$$

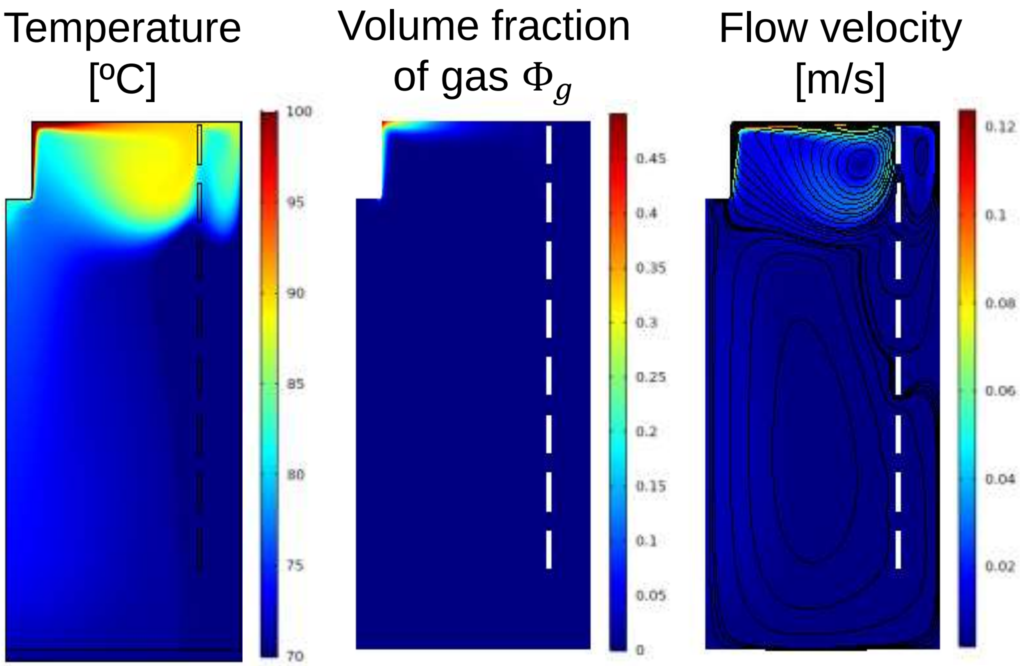
Heat transfer in solid

$$\rho c_p\frac{\partial T}{\partial t}+\nabla\vec{q}=0$$

Results and discussion

Modelling of electrolyte temperature



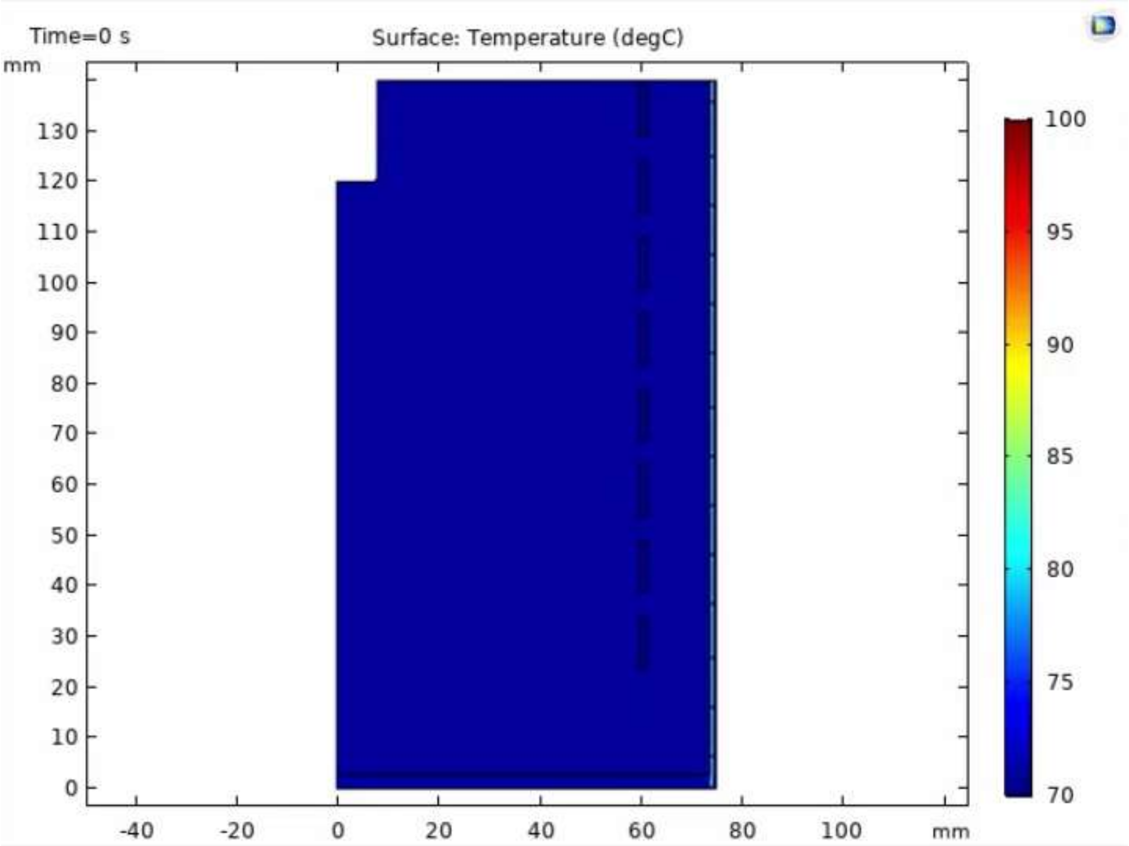


at 30 s of process time

- The model fits well with the experimental measurement of electrolyte temperature
- A bump of the temperature at around 20 s is also observed in the modelled curve
- The temperature, gas fraction and flow velocity of the electrolyte are significantly affected by the transport of heated electrolyte in radial direction

Results and discussion

Modelling of electrolyte temperature



- The temperature simulation explains that in the beginning of the process the heated electrolyte around the workpiece flows to the cathode
- Then the heated electrolyte flows back to the near-workpiece region from the cathode

Summary

- Electrical and thermal measurements can be correlated and reflect the temporal evolution of the gaseous layer around the workpiece

- Determining the power transferred to the substrate revealed three different regions (LT, IT and HT)
    - LT regime : dependent on the immersion depths (~ 335 W at 2 cm) different slope was observed compared to HT, attributed to the increased electrolyte temperature

      *Extra consideration needed for the P_{in} evaluation.
    - HT regime : converging to ~ 180 W → stable gaseous layer

- Higher immersion depth
    - Energy efficiency on the sample reduces down to ~ 20% due to enhanced heating of the surrounding electrolyte
    - Higher surrounding electrolyte temperature → more electrical power consumed

- Temporal evolution of the electrolyte temperature can be explained by the flow of the heated electrolyte using the 2D time-dependent model

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