National Aeronautics and Space Administration

Ames Research Center • Entry Systems and Technology Division

Thermochemically-Closed Sonic-Flow Inversion for Enthalpy and Temperature in Multispecies Arc-Jet Flows

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CREATED AT NASA AMES RESEARCH CENTER, MOFFETT FIELD, CALIFORNIA 94035-1000.
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TP-03, ABLATION I AND AEROTHERMODYNAMICS III (PART 1).

Motivation

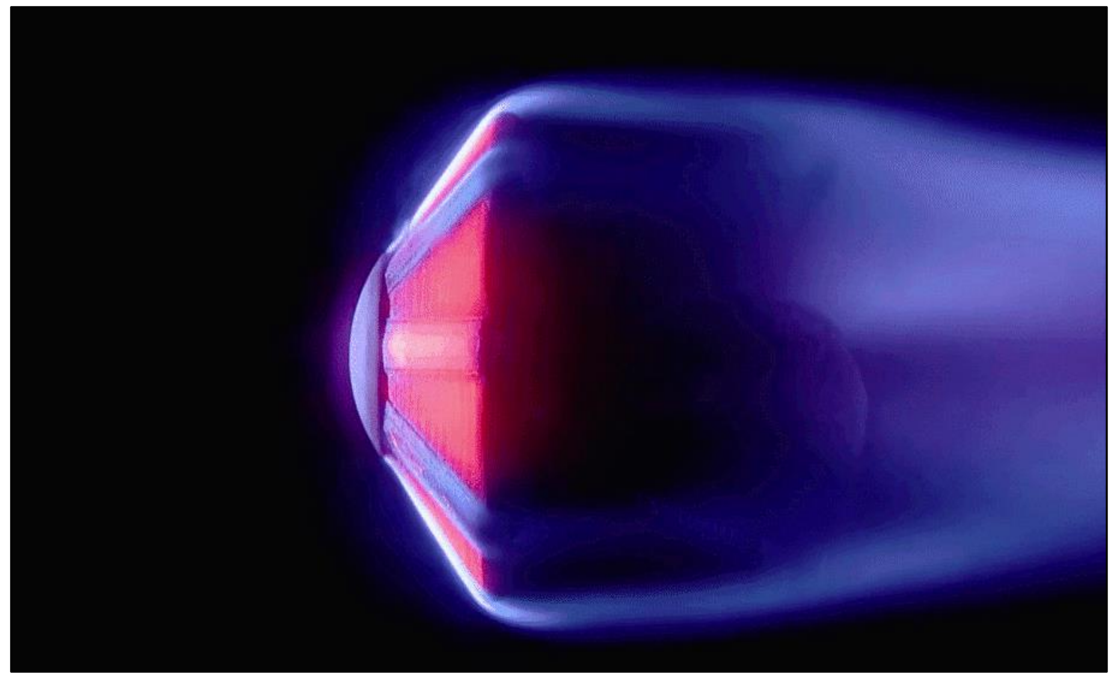
Why should we care about bulk enthalpy?

Bulk enthalpy is used to characterize the total energy content upstream of a nozzle

From an experimental point of view:

- Key for establishing ground-to-flight similarity as it links an arc-jet's total energy content to an equivalent kinetic-energy velocity scale:

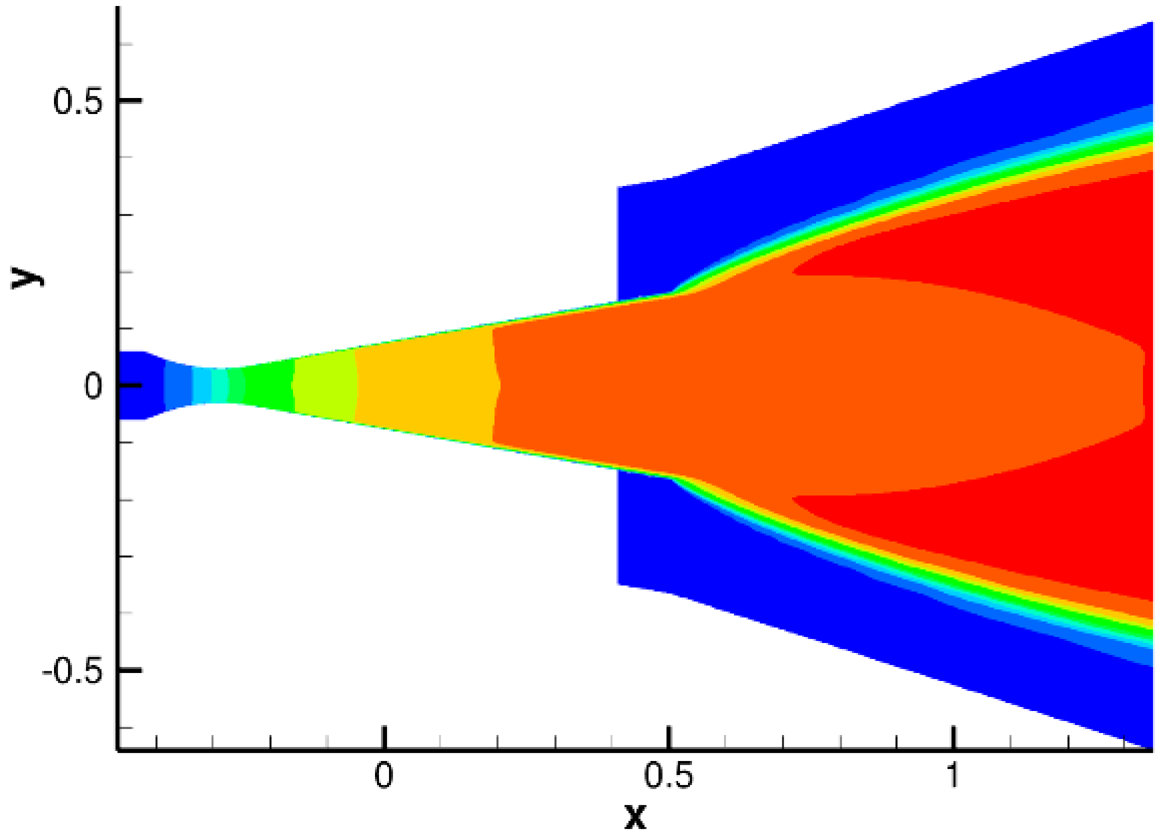
$$h_{\text{bulk}} \cong \frac{v_\infty^2}{2}$$



ADEPT arc-jet test – 60 MW IHF
Credit: NASA/TSF

From a numerical point of view:

- Experimental estimates for h_{bulk} are used as primary in-flow boundary conditions for CFD simulations
- This input affects the accuracy of numerical predictions (e.g., $\dot{q}_0$, p_0), directly impacting any design/engineering decision made thereafter



Palmer et al., AIAA Aviation 2025

Bulk enthalpy quantification techniques

Bulk enthalpy heritage

Bulk enthalpy is not directly measured as a primitive thermodynamic state variable

Techniques:

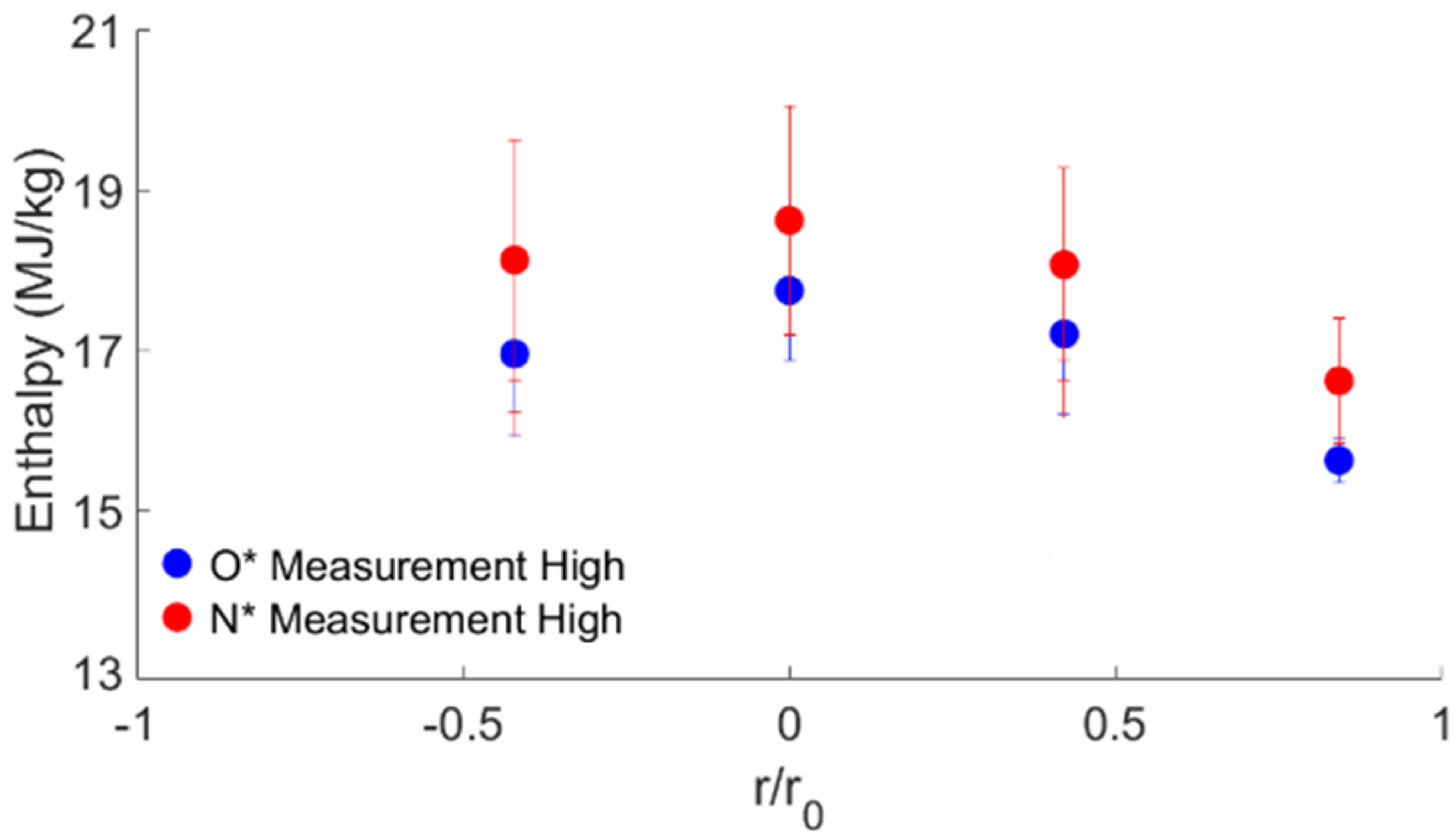
1. Optical & laser diagnostics

2. Energy balance

3. Sonic-flow

1. Optical & laser diagnostics

- High-frequency, non-intrusive local measurements
- Detailed insight into challenging environments (e.g., absorption, fluorescence, scattering)
- To obtain bulk properties from local measurements:
    1. Assumptions about the flow (e.g., axisymmetry)
    2. Meticulous uncertainty quantification and data analysis



TDLAS: Finch et al., AIAA SciTech 2023

Pros	Cons
1. Resolves radial structure	1. Requires optical access
2. Provides local thermochemical information	2. Non-trivial optical setup and alignment
3. High-frequency data acquisition possible	3. Optical setup may be species/gas dependent
4. Non-intrusive	4. Enthalpy can vary by diagnostic/tagged species

2. Energy balance
ASTM E341-08 standard

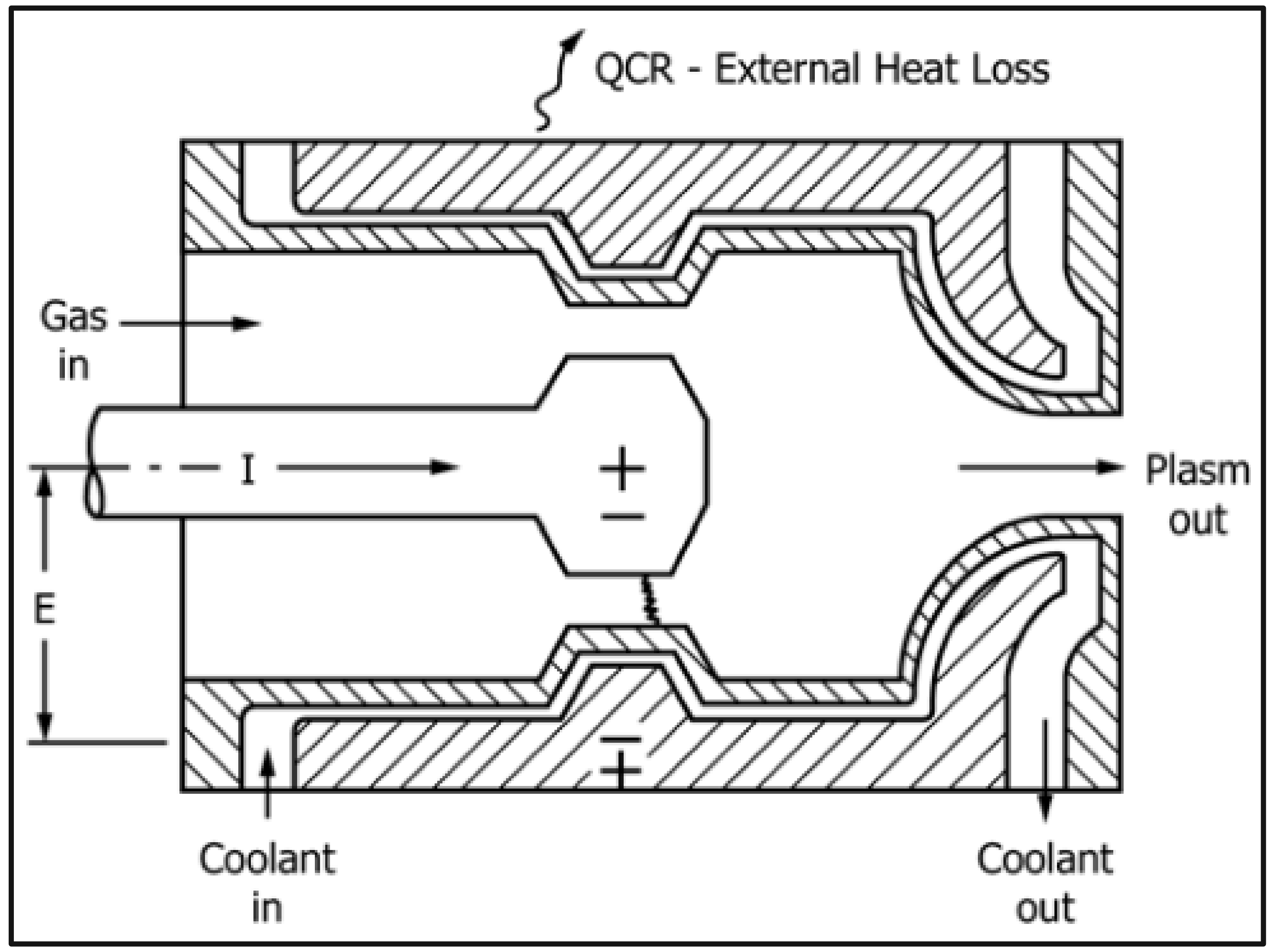
Also known as "enthalpy-by-energy balance" or "EB^2" based on:

1. Energy IN: current and voltage supply

   (minus)

2. Energy OUT: ΔT from the cooling of heater components (cathode, disks, anode, and nozzle)

$$h_{\text{bulk}} = \frac{P_{\text{arc}} - \Delta P_{\text{cool}}}{\dot{m}_{\text{test gas}}}$$



ASTM E341-08 standard 2020

Pros	Cons
1. Simple implementation in small arc-jet facilities	1. Difficult implementation in larger arc-jet facilities
2. Gas-agnostic	2. Large uncertainty if ΔT is low
3. Non-intrusive	

3. Sonic-flow

Developed over many decades based on:

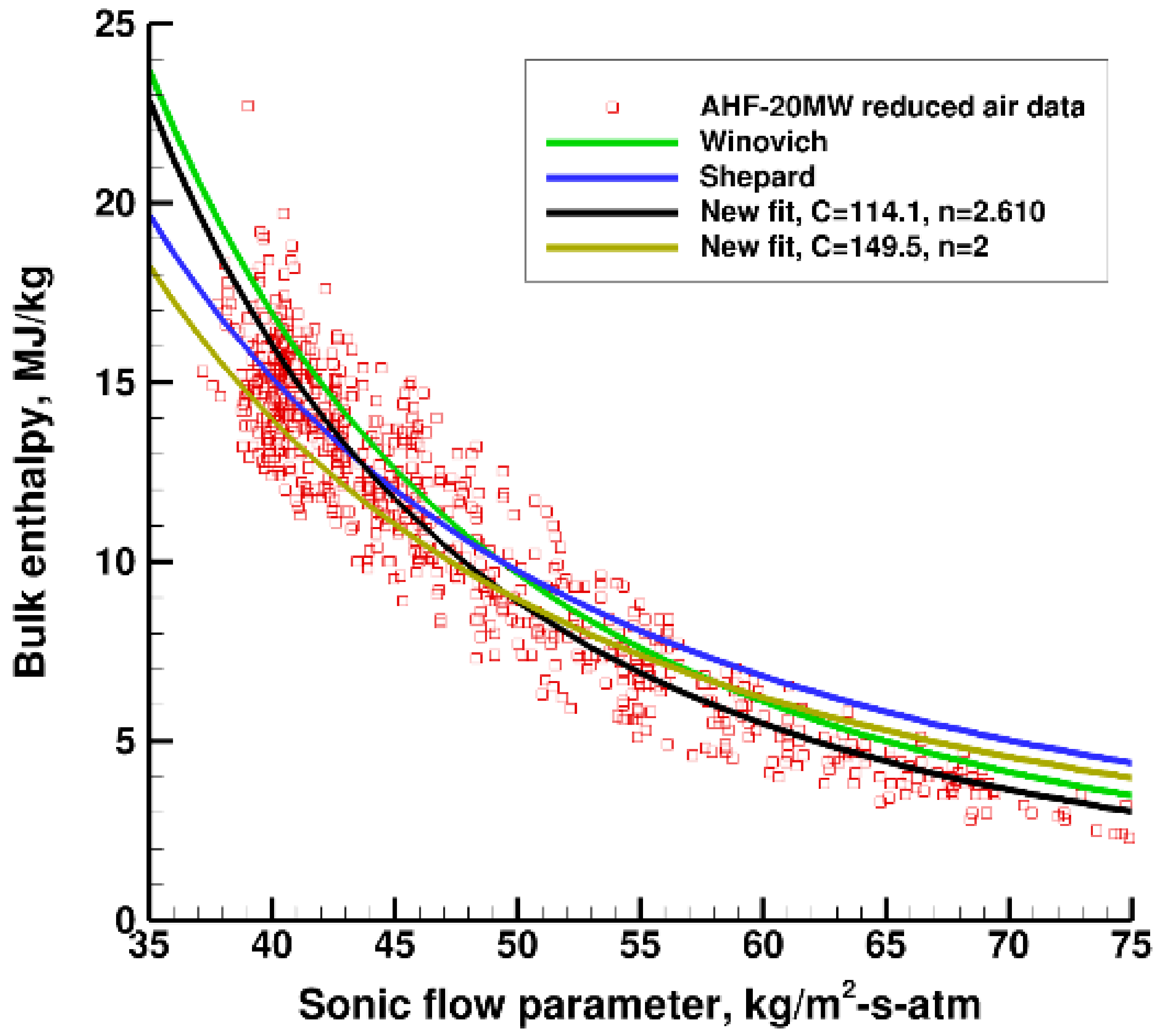
- Compressible flow theory (Winovich 1964)
- Numerical solutions (Shepard 1993)
- EB^2 data (Prabhu 2011; Palmer 2025)

Results can take three general forms:

$$h_{\text{bulk}} \equiv \left(\frac{C}{\sigma}\right)^2 \equiv \left(\frac{C}{\sigma}\right)^n \equiv \left(\frac{C + {}^{\sigma}/_{\sigma_0}}{\sigma}\right)^n$$

where the sonic-flow parameter σ is:

$$\sigma = \frac{\dot{m}_{\text{test gas}}}{p_0 A_t}$$



Palmer et al., AIAA Aviation 2025

Pros	Cons
1. Established in literature	1. Sensitive to scatter in EB^2 data
2. Good initialization for numerical simulations	2. Gas-specific correlations required
3. Non-intrusive	3. Fit form / constraints affect results
4. Fast implementation once correlations are available	4. Limited extrapolation beyond calibration range

TSIF

Thermochemically-Closed Sonic-Flow Inversion Framework

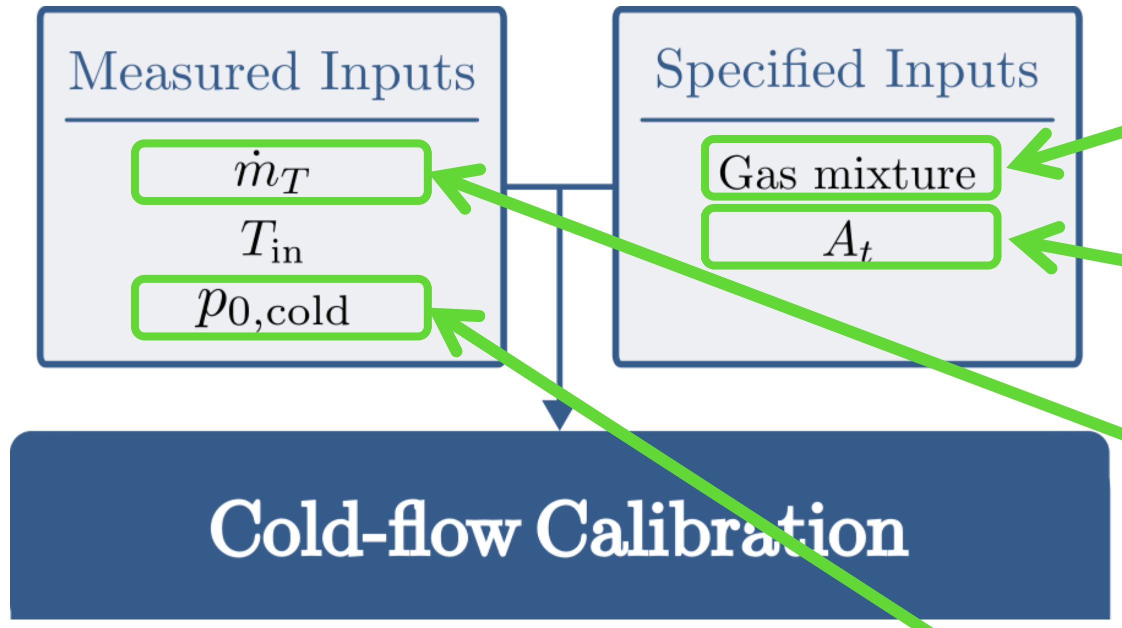
TSIF: Framework Overview

TSIF is comprised of two steps:

1. Cold-flow Calibration
2. Hot-flow Inversion

Cold-flow Calibration | **Hot-flow Inversion**

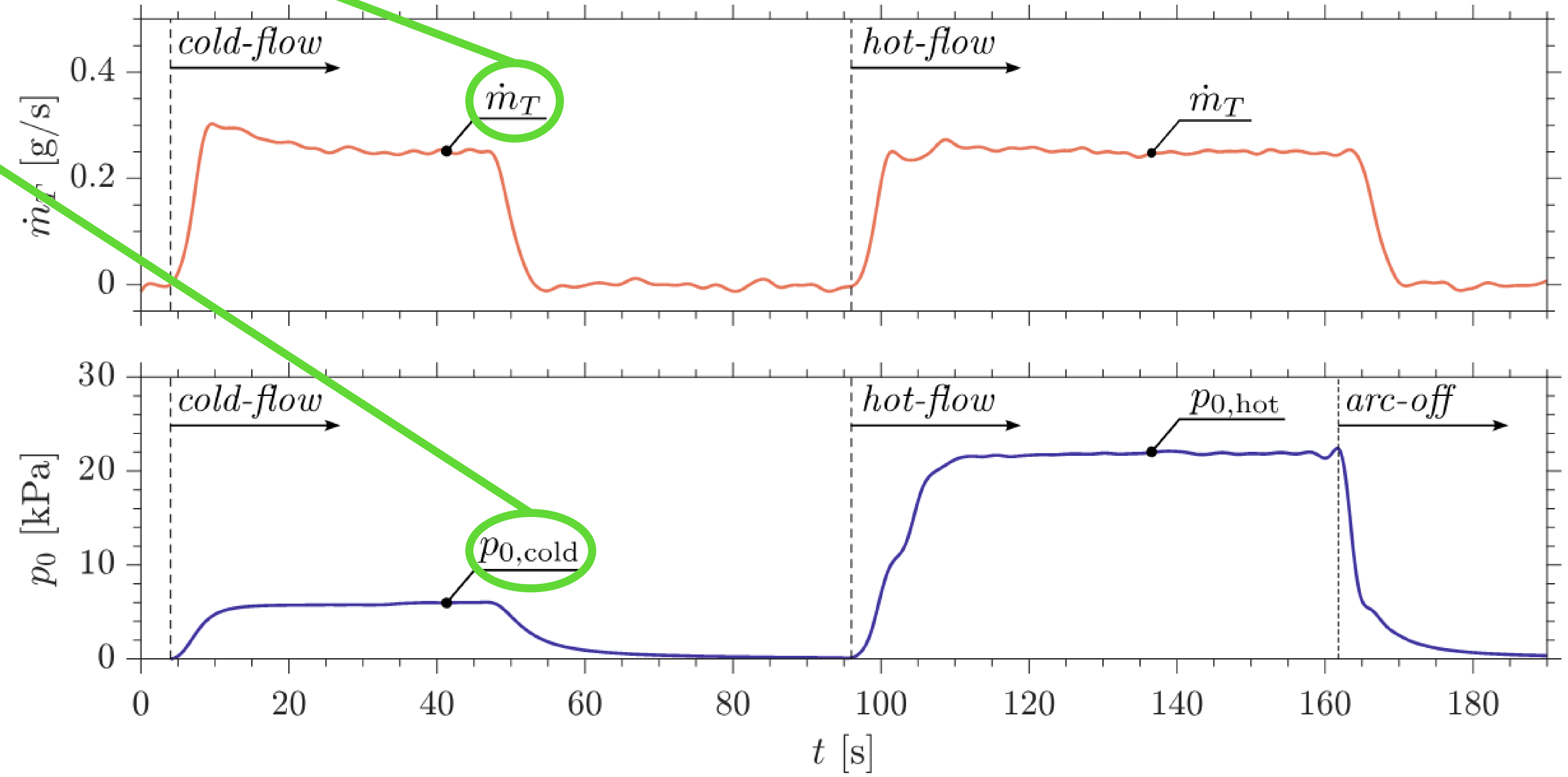
Step 1: Cold-flow Calibration
Inputs



e.g., CO_2 (95%), N_2 (5%)

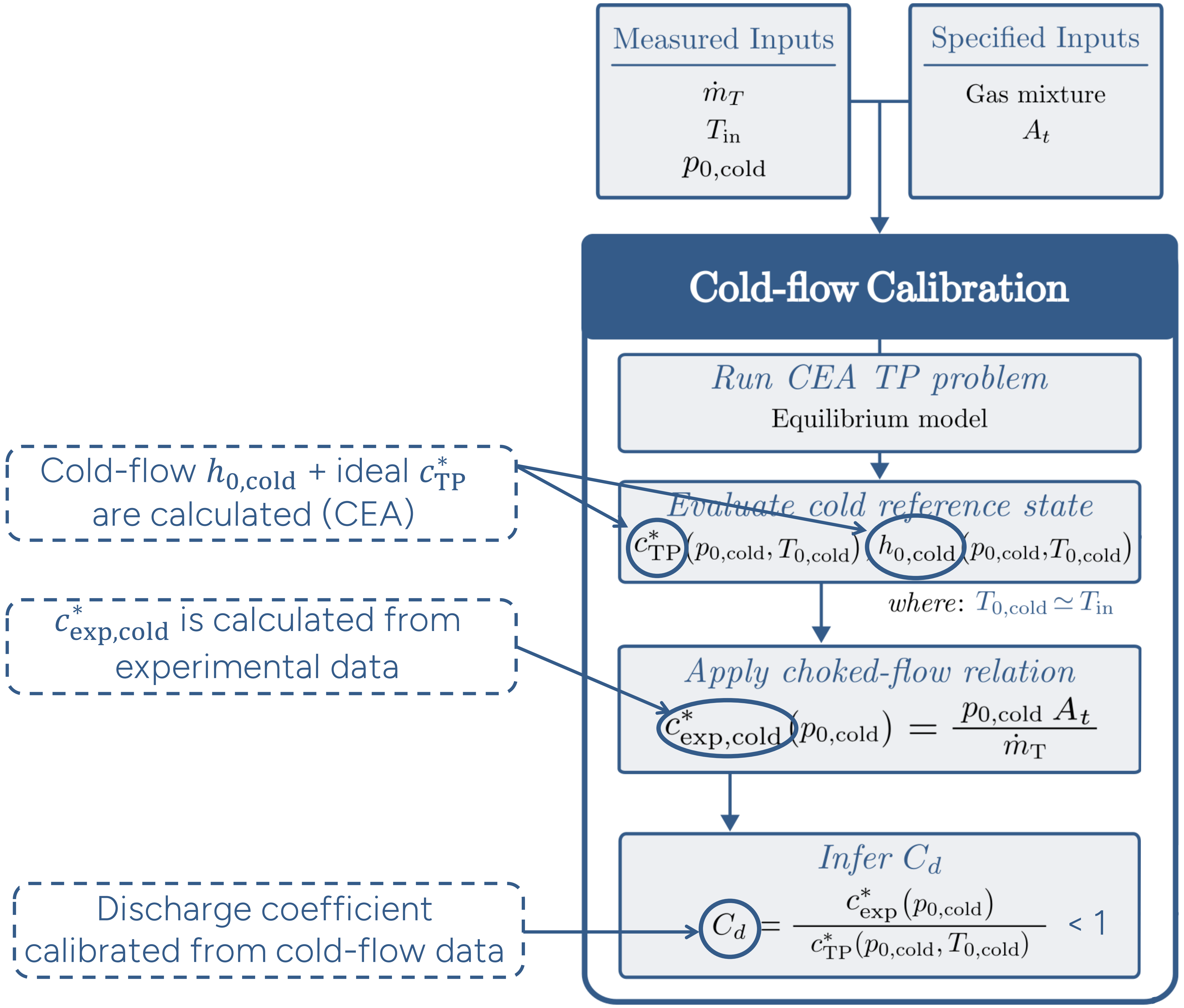
Nozzle throat area

$\dot{m}_T$ during cold-flow and hot-flow must be the same (cold-flow can be done before or after arc-on)



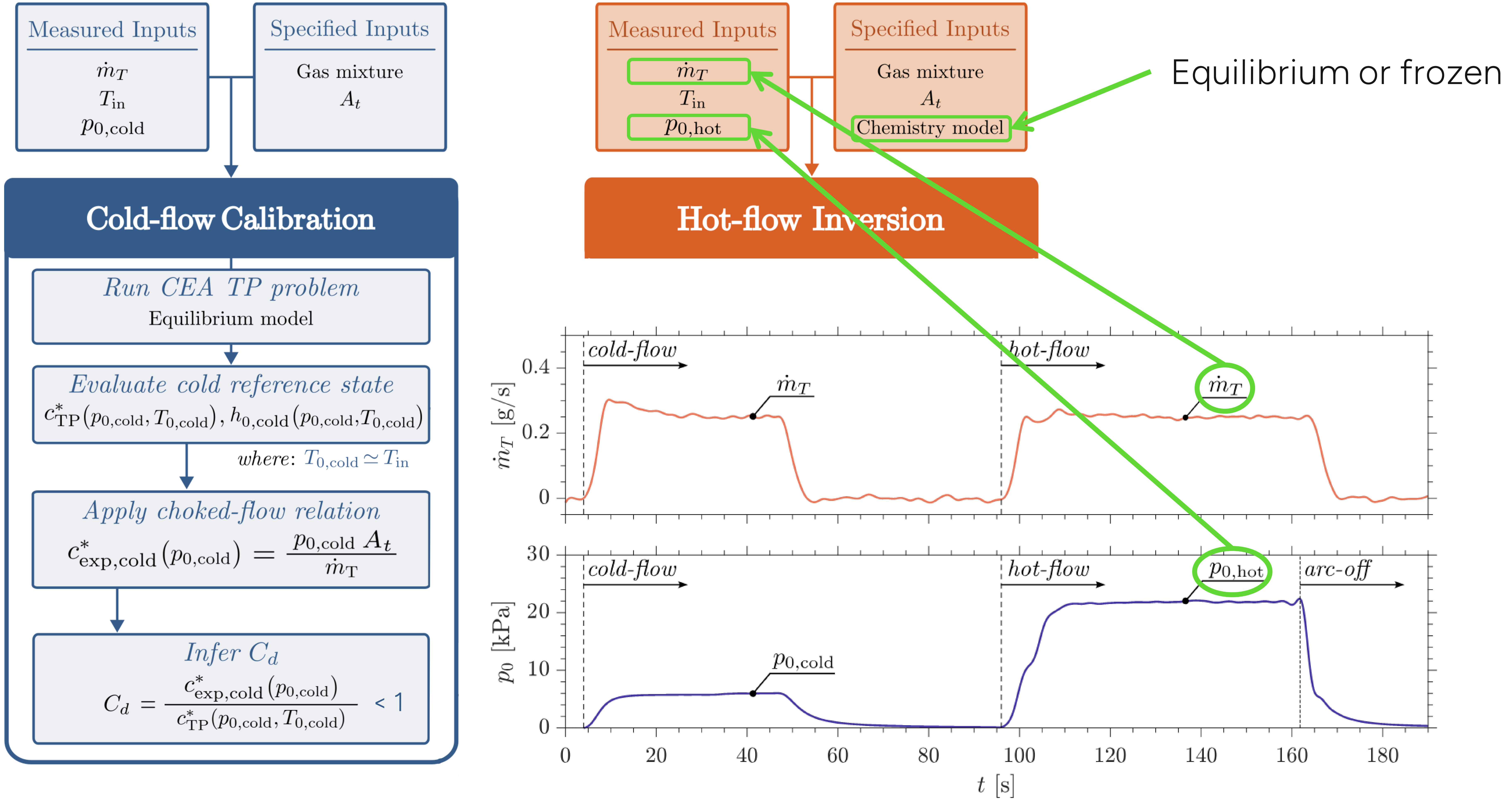
Step 1: Cold-flow Calibration

CEA equilibrium case using Temperature–Pressure (TP) problem



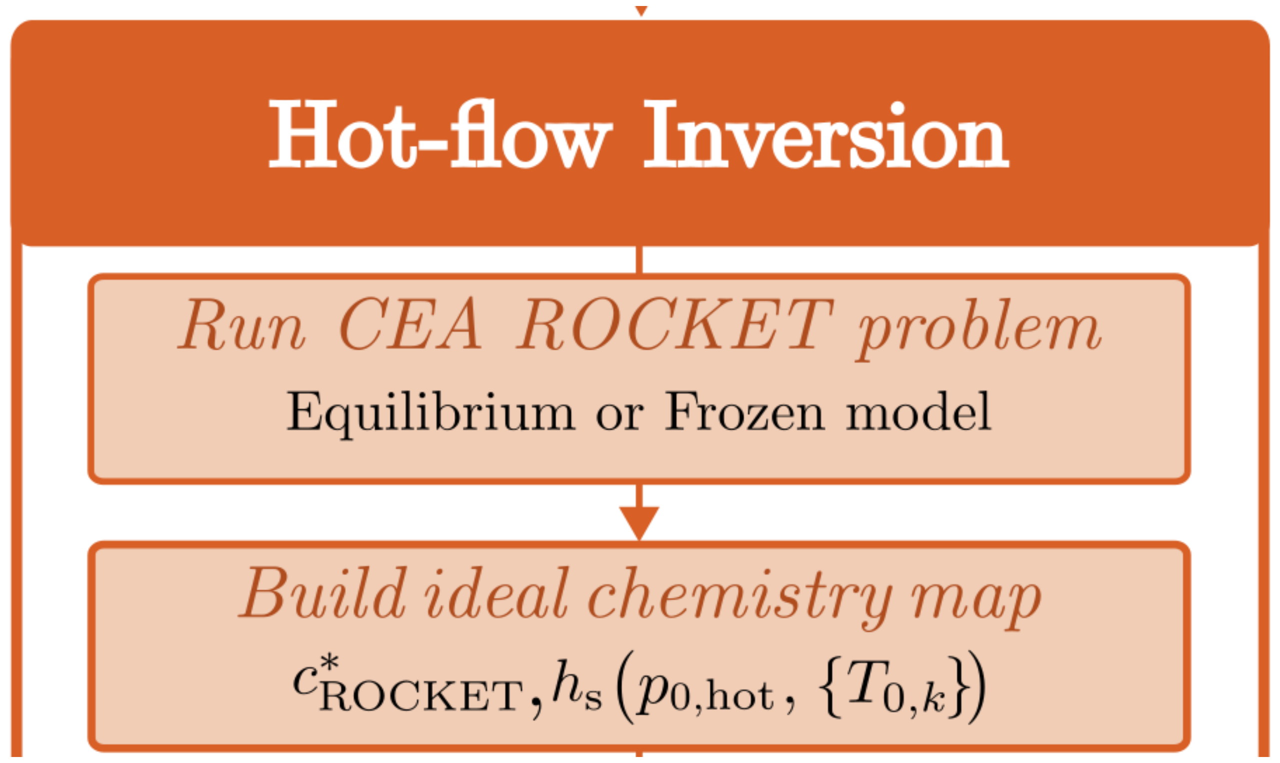
Step 2: Hot-flow Inversion

CEA using ROCKET problem



Step 2: Hot-flow Inversion

3D visualization of c^*–h_0 manifold (CO_2/N_2 mixture)



INPUTS:

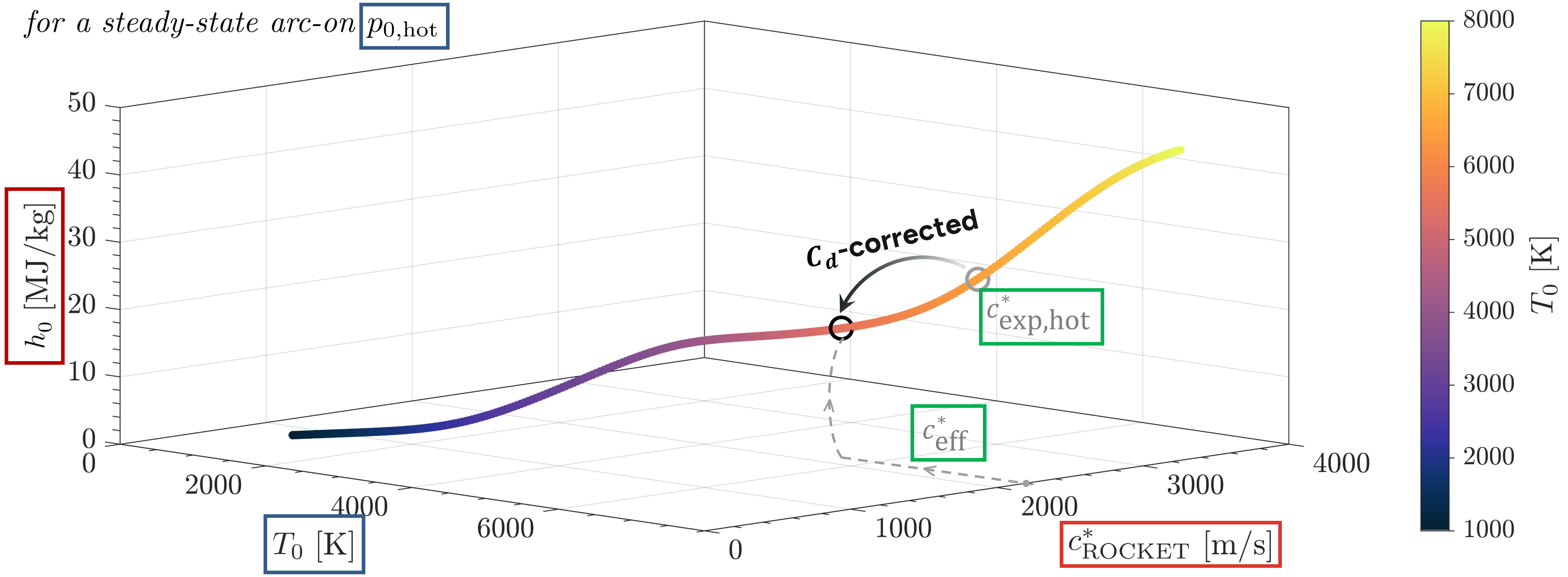
- measured/constant $p_{0,\mathrm{hot}}$
- gridded T_0 ($1000 \leq T_0 \leq 12{,}000$ K)

OUTPUTS:

- c^*_{ROCKET}
- h_0

FINAL STEPS:

- Compute $c^*_{\mathrm{exp,hot}} = p_{0,\mathrm{hot}} A_t / \dot{m}_{\mathrm{T}}$
- Use C_d to correct $c^*_{\mathrm{exp,hot}}$ to c^*_{eff}



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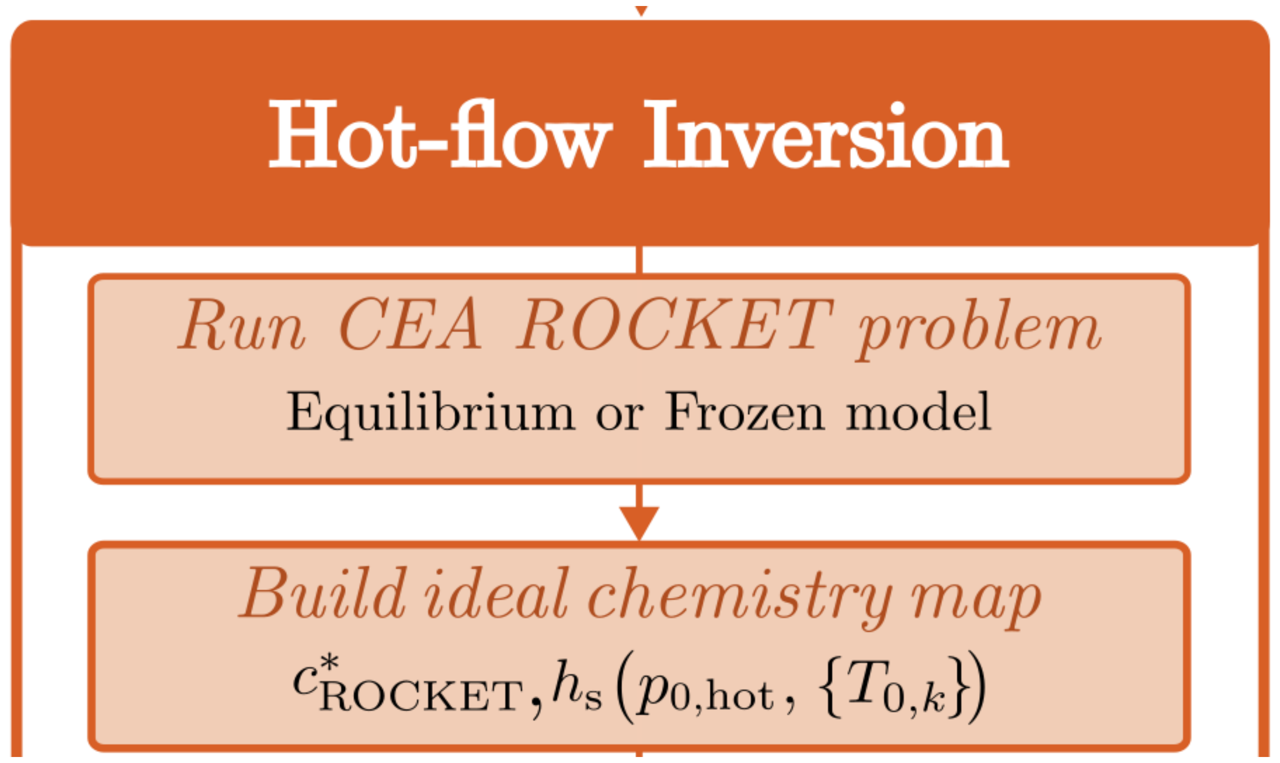

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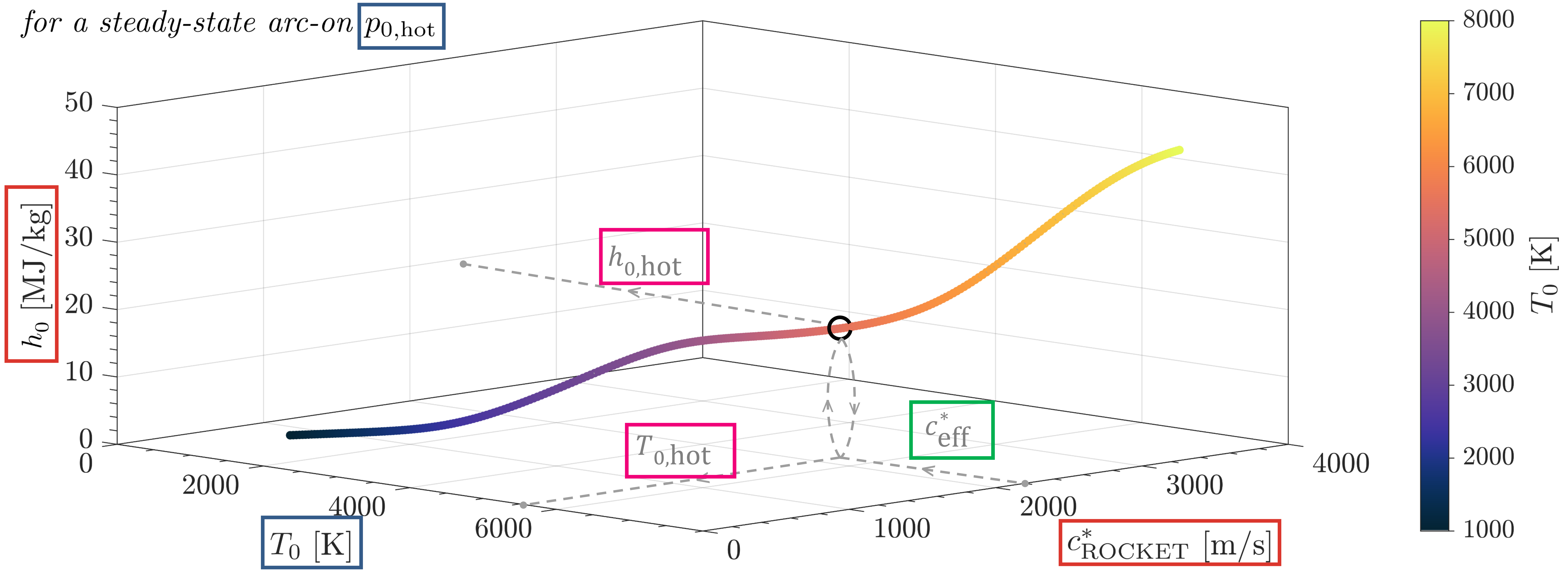
- Infer $h_{0,\mathrm{hot}}$ and $T_{0,\mathrm{hot}}$ by inverting at c^*_{eff} query point



Uncertainty analysis

$$\left(\frac{\sigma_{c^*_{\mathrm{eff}}}}{c^*_{\mathrm{eff}}}\right)^2 \approx \left(\frac{\sigma_{C_d}}{C_d}\right)^2 + \left(\frac{\sigma_{p_{0,\mathrm{hot}}}}{p_{0,\mathrm{hot}}}\right)^2 + \left(\frac{\sigma_{A_t}}{A_t}\right)^2 + \left(\frac{\sigma_{\dot{m}_{\mathrm{T}}}}{\dot{m}_{\mathrm{T}}}\right)^2$$

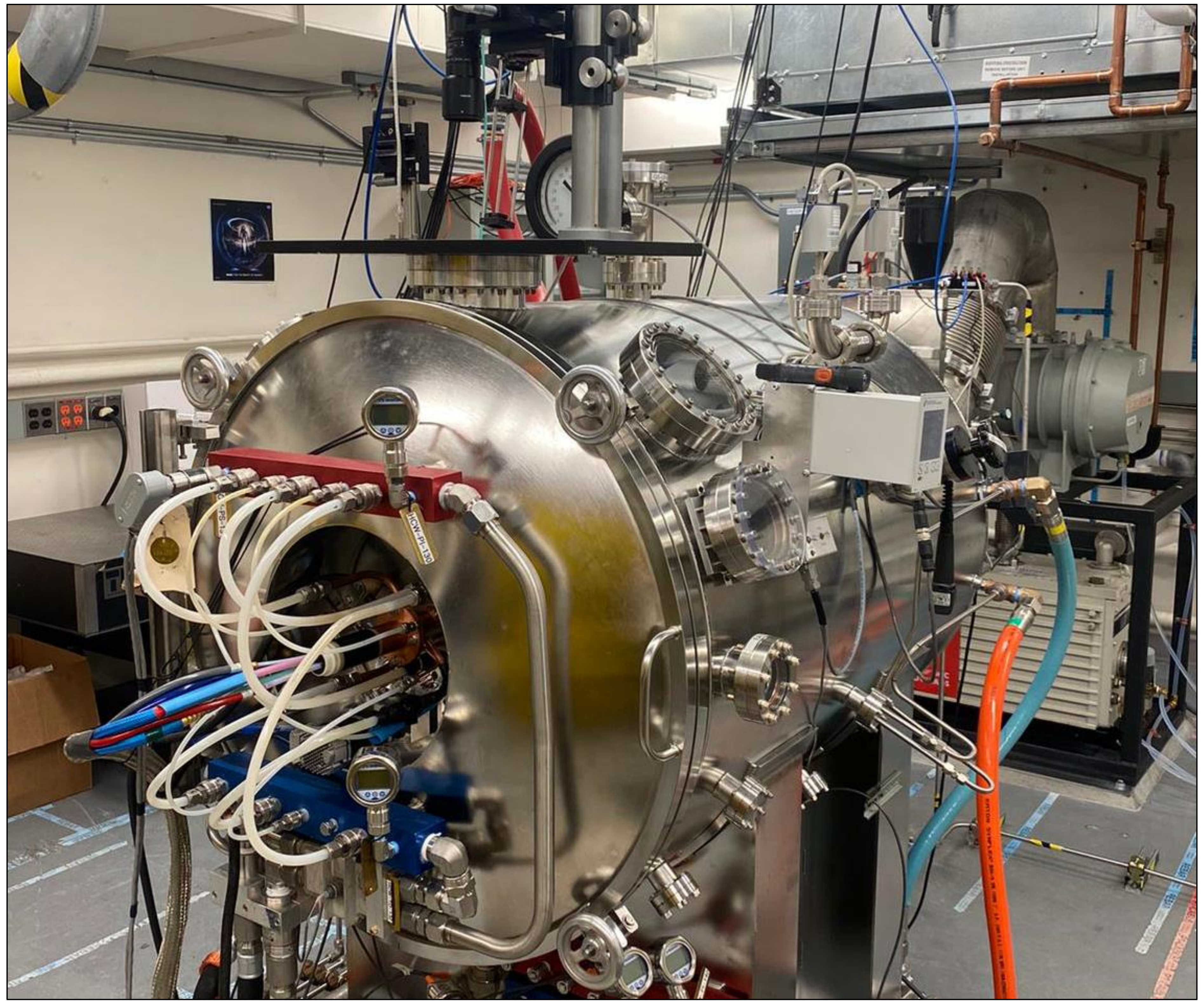
$$\sigma_{h_{0,\mathrm{hot}}} \approx \left| \left(\frac{\partial h_0}{\partial c^*_{\mathrm{ROCKET}}}\right)_{p_{0,\mathrm{hot}}} \right| \sigma_{c^*_{\mathrm{eff}}}$$

Bulk enthalpy

$$h_{\mathrm{bulk}} = \Delta h_0 = h_{0,\mathrm{hot}} - h_{0,\mathrm{cold}}$$

Experimental details

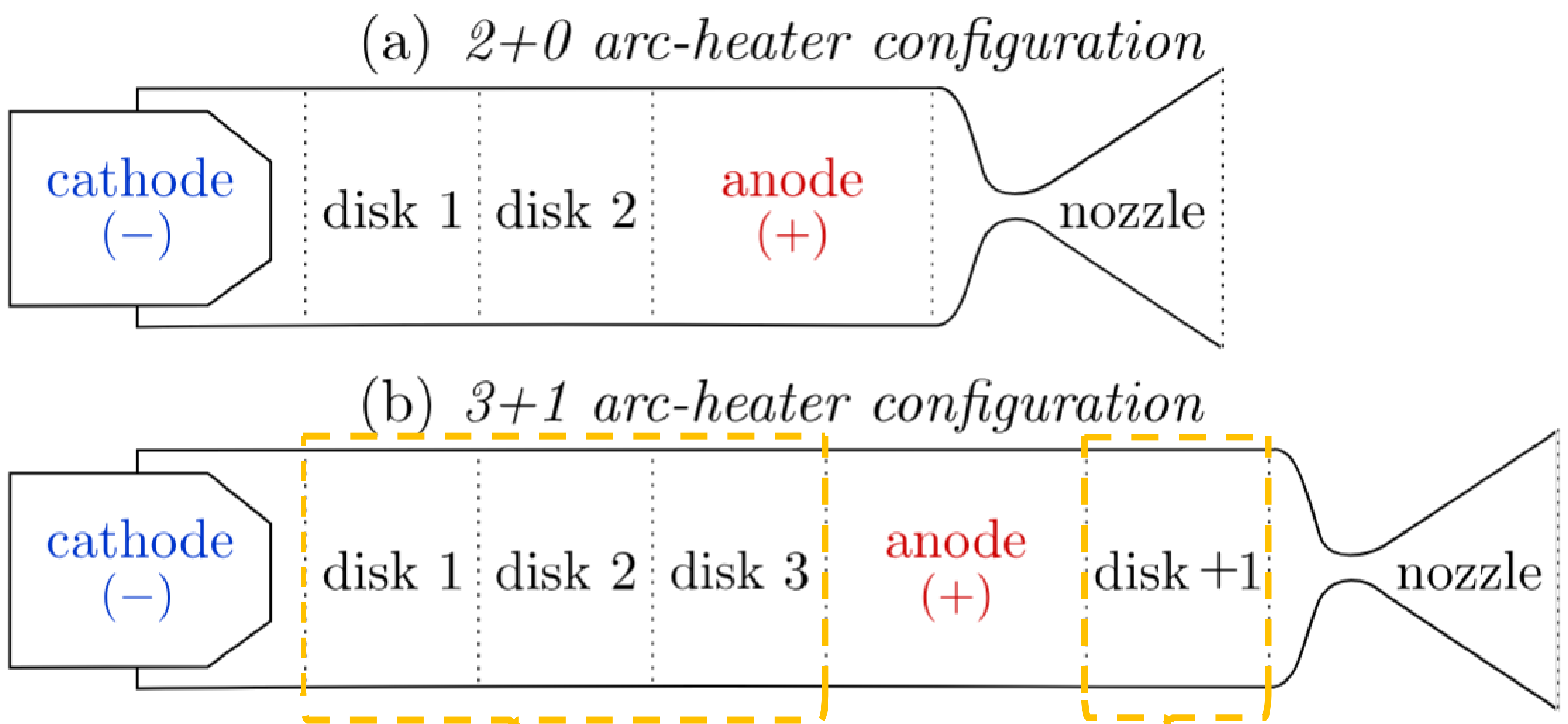
30 kW mARC II: segmented-constricted arc-jet



AIAA papers:

- MacDonald et. al, Aviation 2023, DOI: 10.2514/6.2023-3298
- Rodrigues at. al, Aviation 2024, DOI: 10.2514/6.2024-3553
- Rodrigues et. al, SciTech 2025, DOI: 10.2514/6.2025-2443
- Palmer et al. Aviation 2025, DOI: 10.2514/6.2025-3480
- Edwards et. al, Aviation 2026 (this conference)
- Rodrigues, Journal of Thermophysics and Heat Transfer, 2026 (accepted)

Two configurations: "2+0" and "3+1"



First digit: # of disks between cathode + anode

Second digit: # of disks between anode + nozzle (a.k.a. mixing plenum)

Test conditions:

- Test gases: CO_2/N_2 (95%/5%), Air (100%), N_2 (100%)
- Arc current: 40–200 A
- Total flow rate: 0.25–0.80 g/s

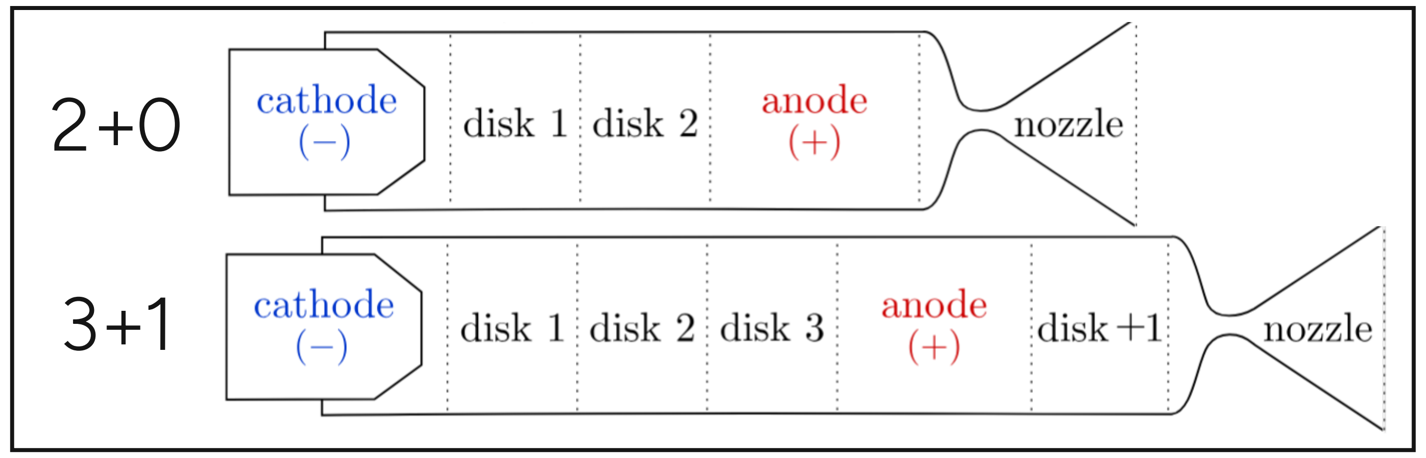
Results

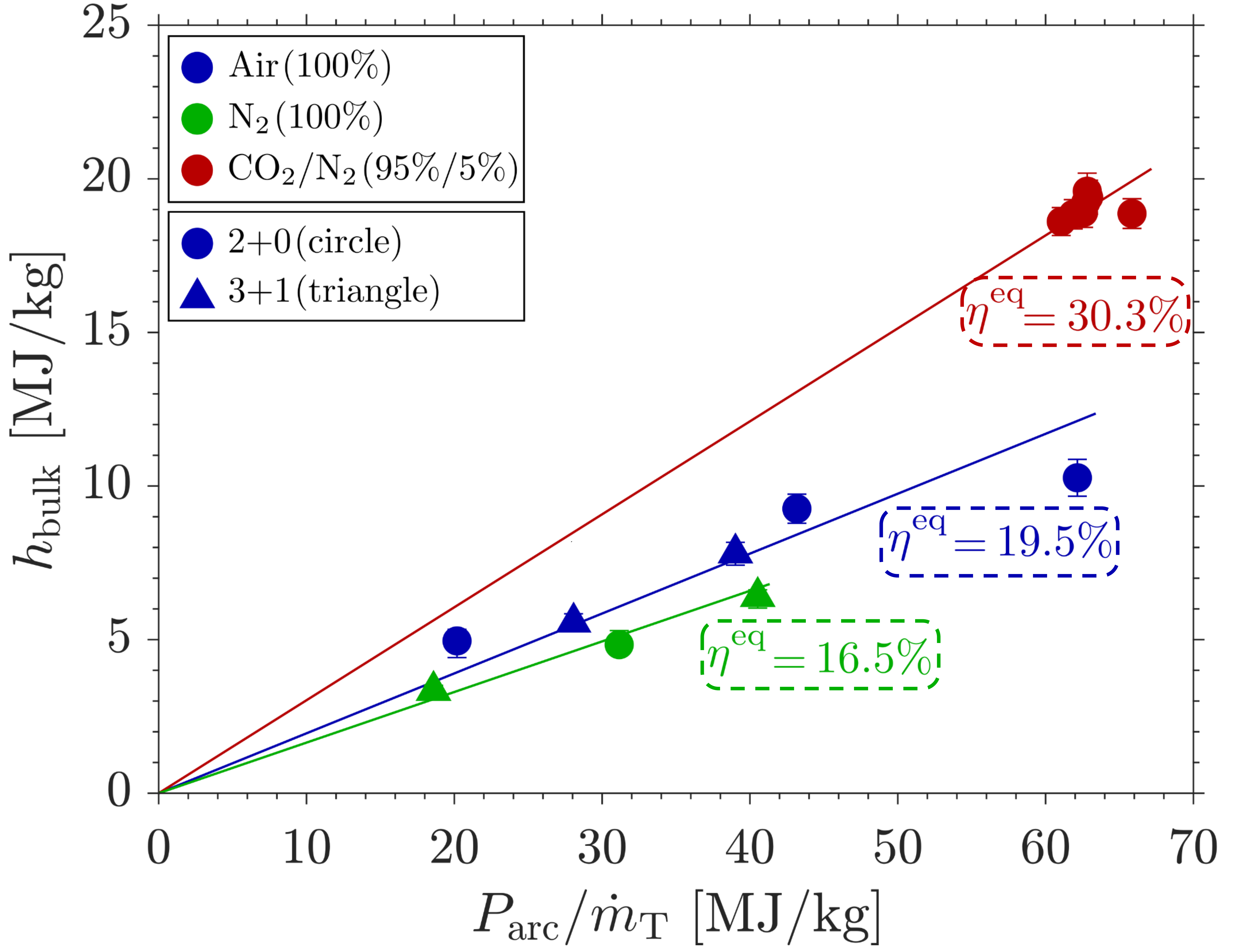
Inferred bulk enthalpy h_{bulk}

Bulk enthalpy increases ~linearly with specific energy input

- Gas dependence follows expected trends:
  CO_2/N_2 > air > N_2
- More data needed to assess linearity
- Assuming a linear scaling for each mixture enables inference of TSIF-based arc-jet efficiency:

$$h_{\text{bulk}} = \eta \left(\frac{P_{\text{arc}}}{\dot{m}_{\text{T}}} \right)$$



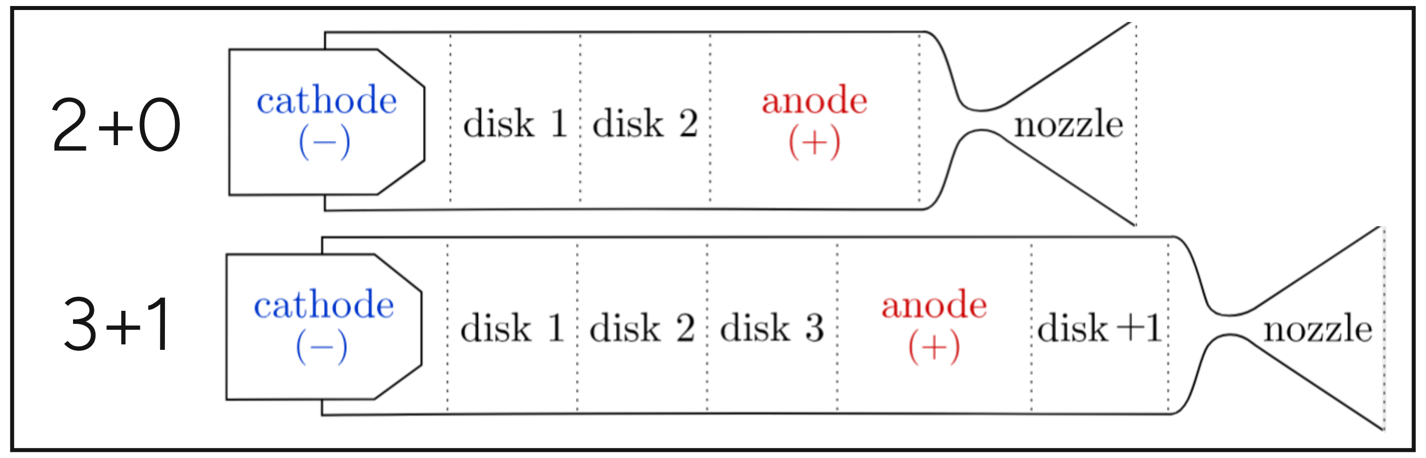


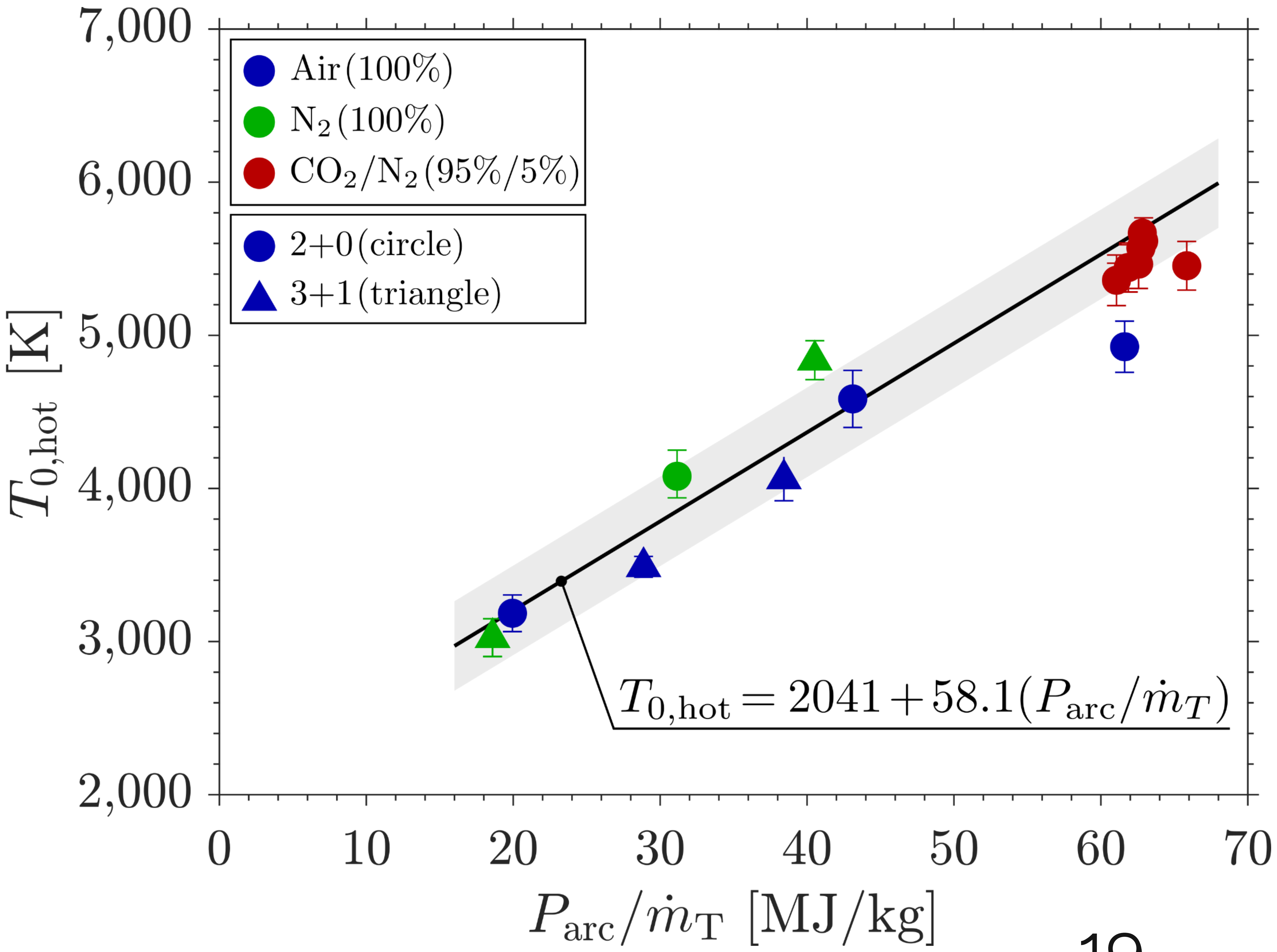
Inferred total temperature $T_{0,\mathrm{hot}}$

Across the tested conditions, total temperature varies approximately linearly with specific energy input

- Data for air, N_2, and CO_2/N_2 collapse reasonably well onto a common local trend

- The linear fit should be interpreted as a 'back-of-the-envelope' relation over the tested range, not a physical low-energy limit





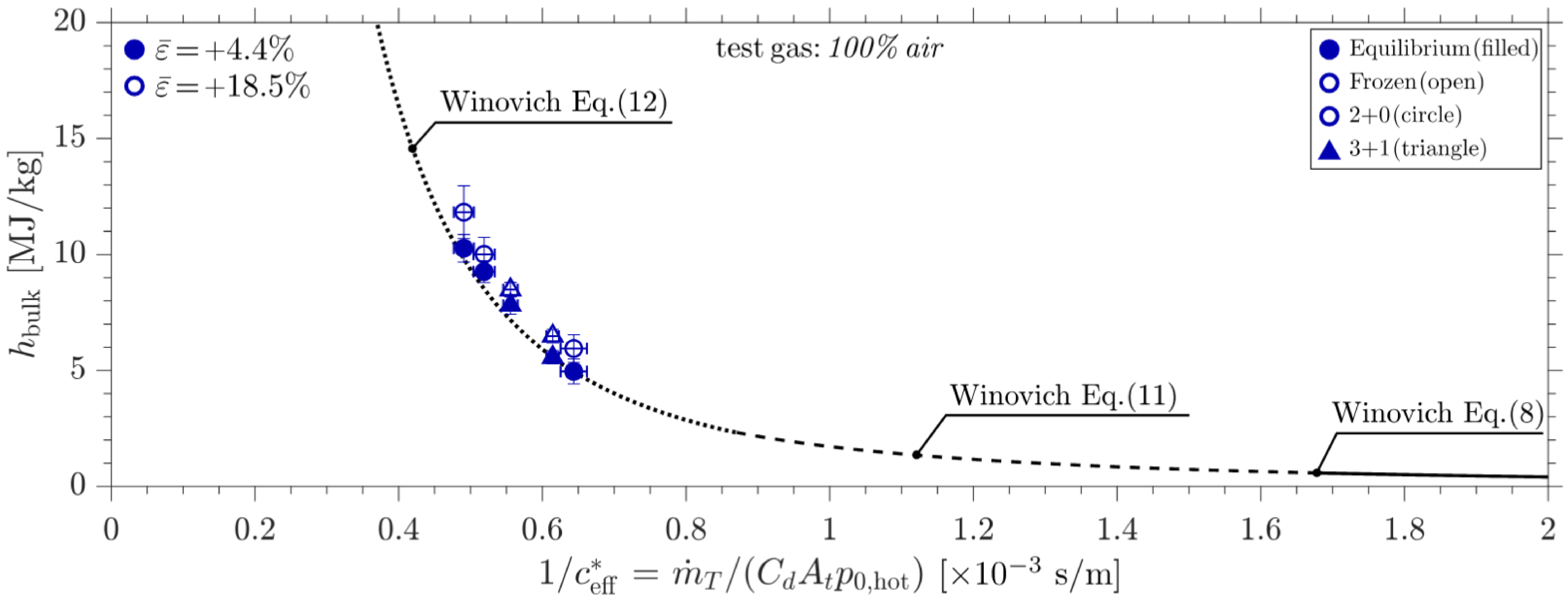
Recovering the classic sonic-flow scaling for air

Frozen–air chemistry (○): produces a uniform upward shift (+18.5%):

- Suppressed recombination – higher bulk enthalpy is needed for the same choked flow constraint
- Highlights thermochemical effects rather than data scatter or framework error

Equilibrium–air chemistry (●): agrees with Winovich scaling (+4.4%):

- Winovich equilibrium behavior emerges naturally without empirical fitting
- Configuration (2+0 vs 3+1) does not affect the solution



Concluding Remarks

Conclusions

1. Framework:
   - TSIF recasts Winovich's (1964) work by coupling first-principles compressible flow with an open-source thermochemical solver to infer h_{bulk} and T_0 in c^* space
   - Mixture-flexible with selectable equilibrium/frozen chemistry models, clear uncertainty propagation, and explicitly quantified facility-specific discharge calibration
2. Physical consistency:
   - Inferred thermochemical states follow expected trends
   - Demonstrated sensitivity to multi-species gas composition and chemistry closure model
   - Recovered Winovich's equilibrium–air scaling without any constraints
3. Practical impact:
   - Only requires measured upstream quantities: total flow rates and total pressures!
   - Can be applied to choked-flow facilities with readily available data at no added cost

Future Work

1. Apply TSIF to other arc-jet facilities' datasets:
   - Please contact me to get bulk enthalpy estimates! (jocelino.rodrigues@nasa.gov)
2. Compare TSIF with other enthalpy quantification methods:
   - ASTM E341 for upstream bulk enthalpy
   - ASTM E637 for downstream centerline enthalpy
3. Feed TSIF data into numerical simulations:
   - Analyze measured and predicted outputs – how do they compare?
4. Submit TSIF for balloting as new ASTM standard practice:
   - Chair of E21.08 Thermal Protection subcommittee suggested idea
   - Submitted work item — currently being drafted before going to ballot

Customer testing

mARC II has officially begun customer testing this year (SpaceX, Blue Origin)

If you are interested in low-cost ground-testing at Ames, please contact our POC for more details:

National Aeronautics and Space Administration

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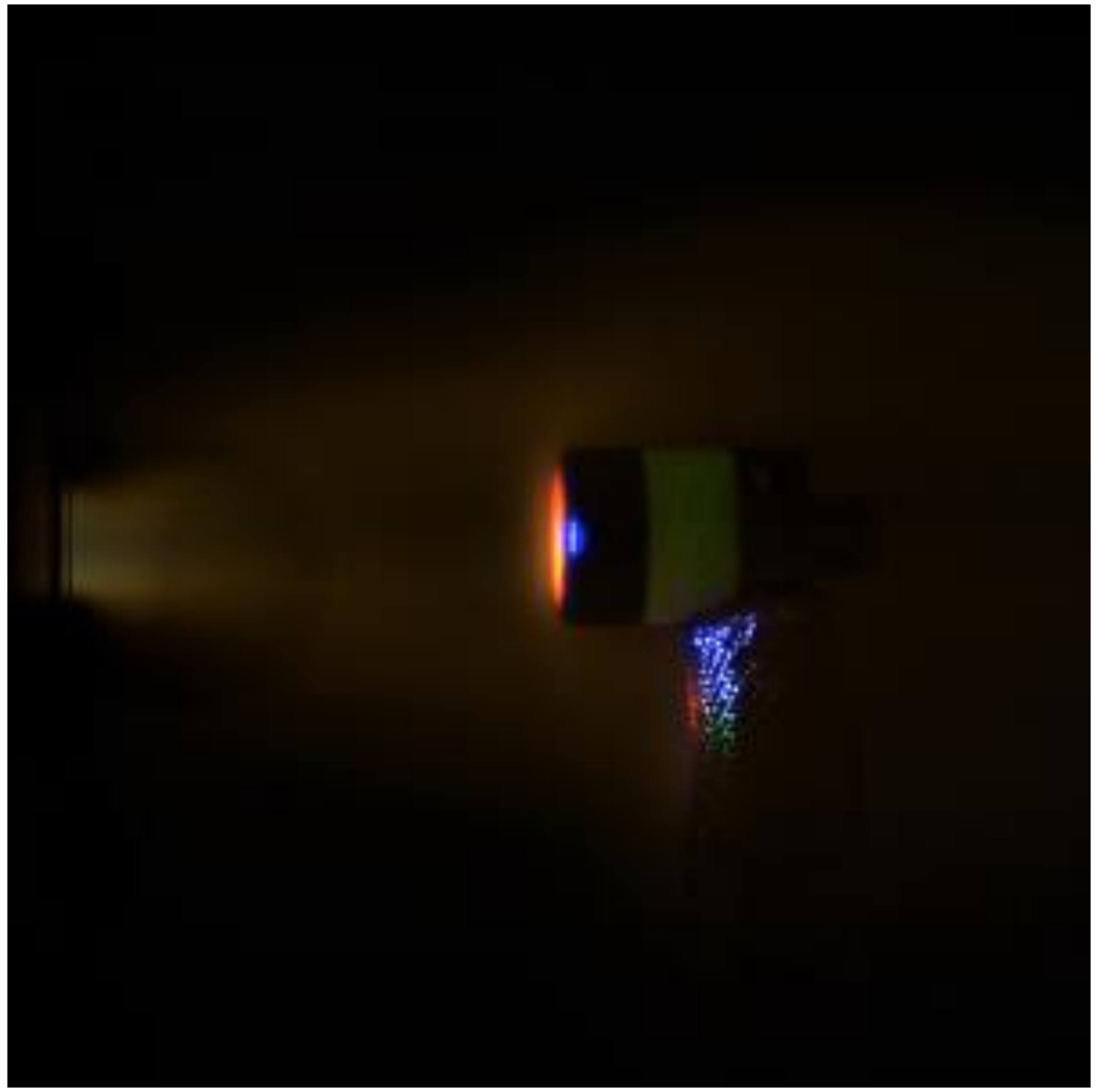

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Thank you!

for the benefit of all

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