Clean Energy Systems Integration Lab

Washington State University

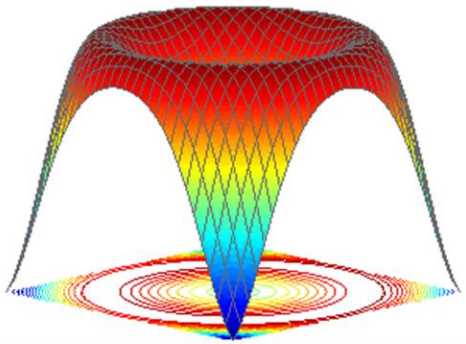
# FC-GT Hybrids

- Modeling High Temperature Fuel Cells
- Modeling Gas Turbines
- Dynamically Controlling a FC-GT Hybrid

# Introduction

## » Advanced Technology Traits:

- > Ultra-high Efficiency
- > Ultra-low Emissions
- > Rapidly Responsive
- > Fuel Flexible



Physical Models

FC-GT Hybrid

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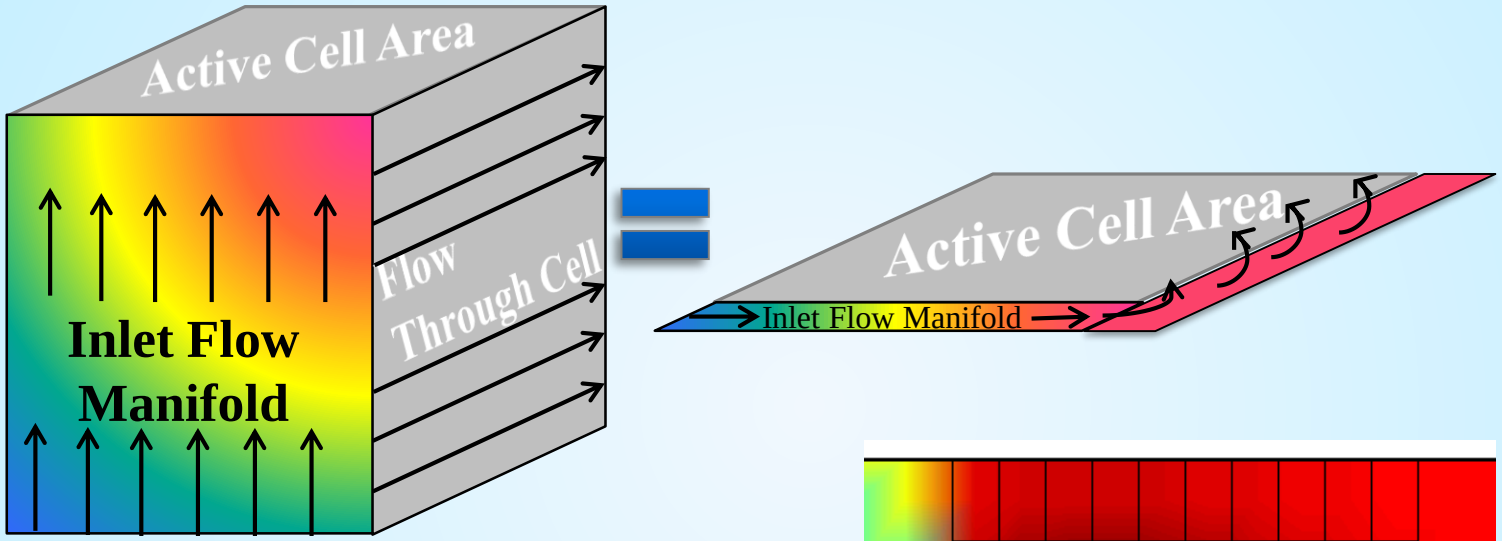
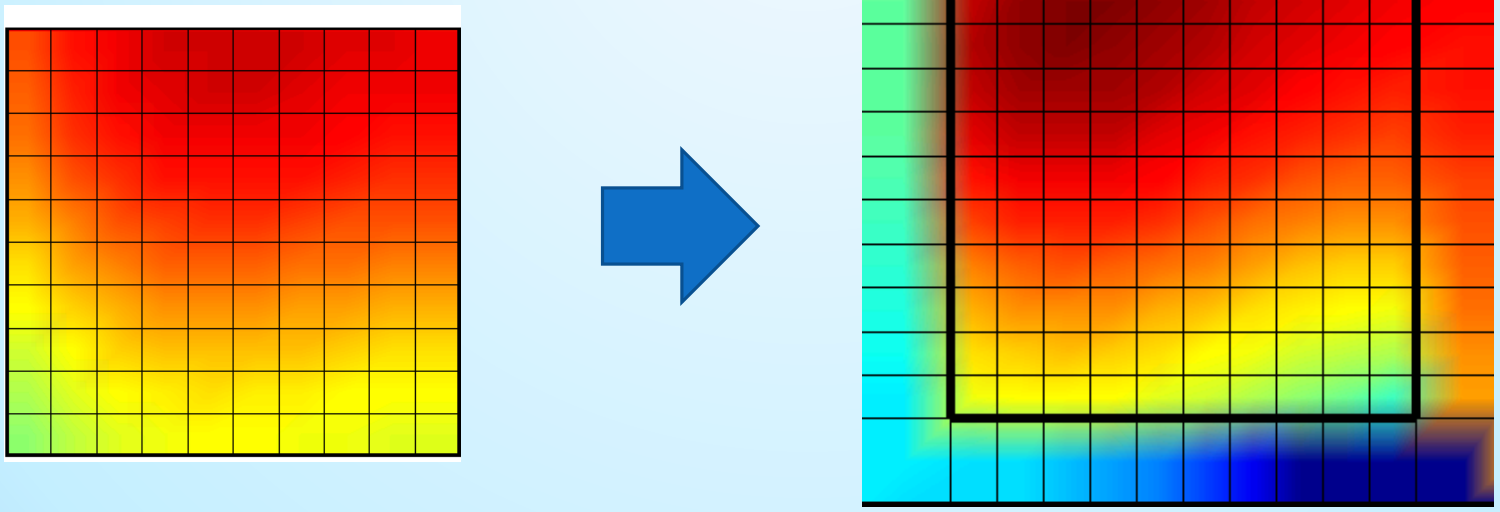
# Quasi-3D Geometry



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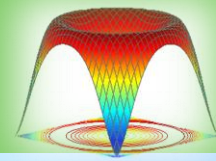
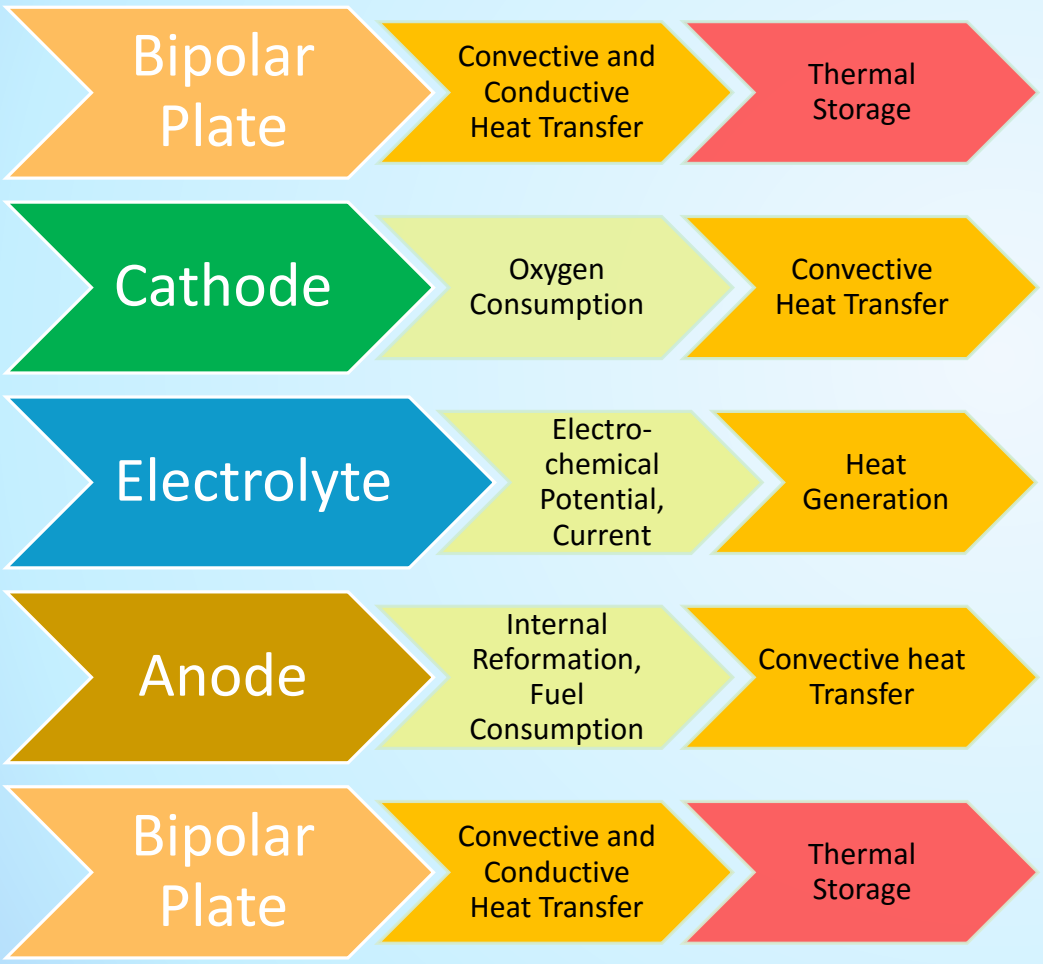
# Physical Modeling






- **Conservation of Species:**

$$\frac{R_{Ref+Consume} + (\dot{n} \cdot \mathrm{X}_i)_{in-out}}{P\forall / R_U T} = \frac{d\mathrm{X}_i}{dt}$$

- **Conservation of Energy:**

$$\frac{\sum Q_i + \dot{q}}{C_p m} = \frac{dT}{dt}$$

- **Conservation of Mass:**

$$\frac{(\dot{n}_{in} - \dot{n}_{out}) \cdot R_u \cdot T}{\forall} = \frac{dP}{dt}$$

- **Electrochemistry:**

$$\eta_{cath} = \frac{R_U T}{4F} ln \frac{j * c_R^*}{j_L * c_R^0}$$

$$\eta_{ohm} = j \frac{t^M T}{K e^{-\Delta G_{act}/(RT)}}$$

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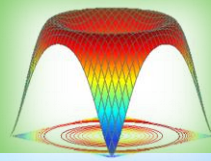
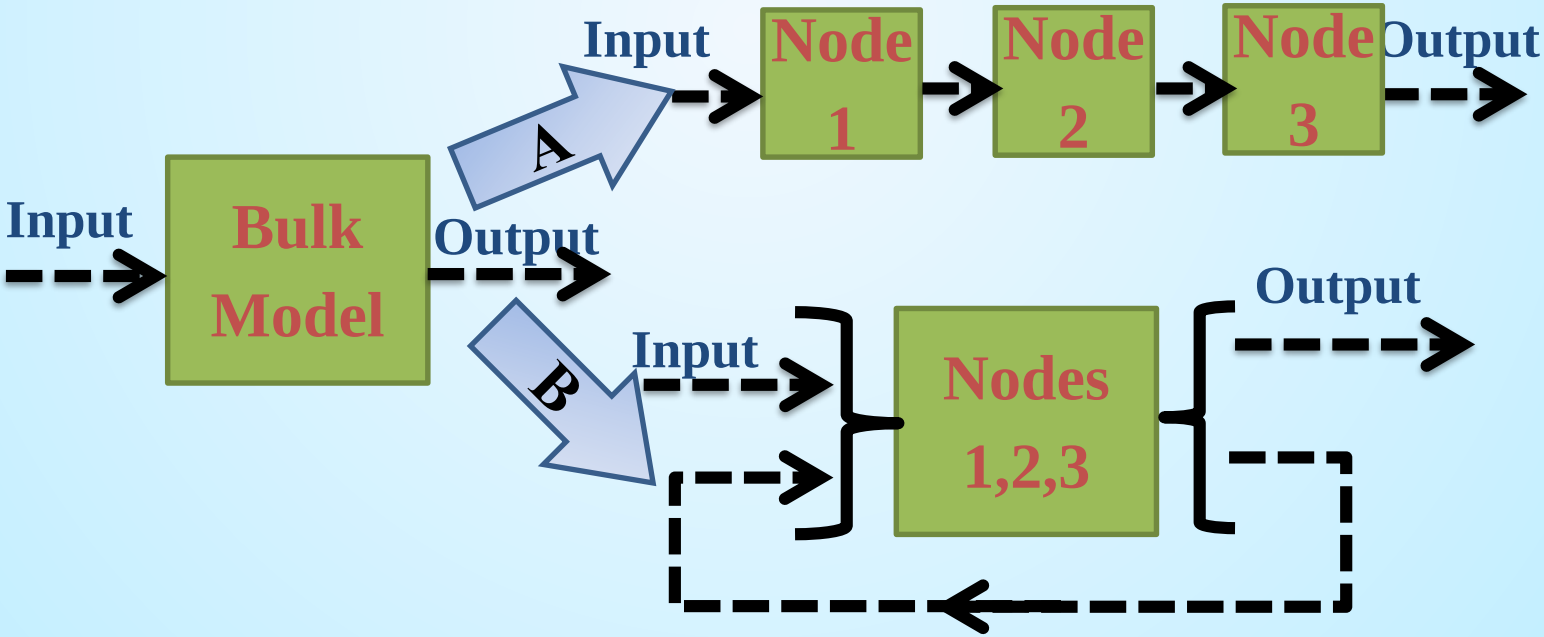
# Spatial Discretization



- Novel vector mathematics approach
  - Scalable resolution, 1-D, 2-D or 3-D
  - Variable flow geometry, Co-flow, Counter-flow, Cross-Flow, etc.
  - Smaller file size, loads quicker
  - Faster computation, $O(n^2) \rightarrow O(n)$

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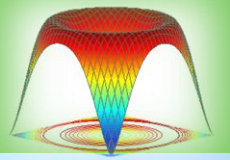
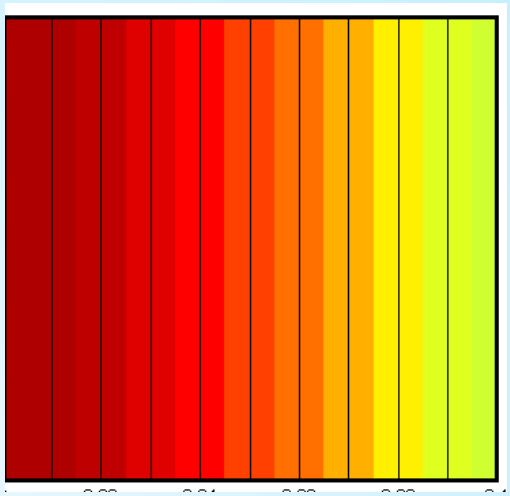
# Spatial Resolution



**Bulk**

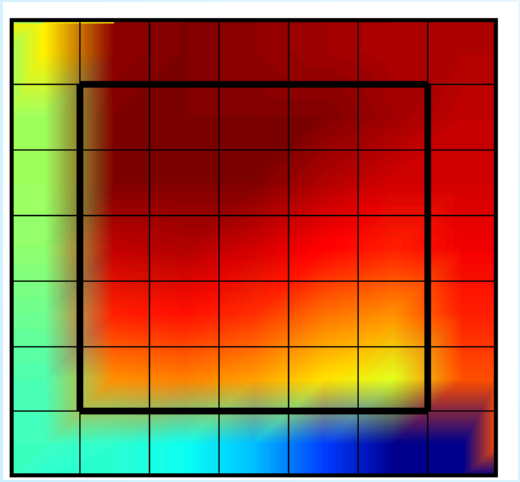
**1x10**



Air Direction

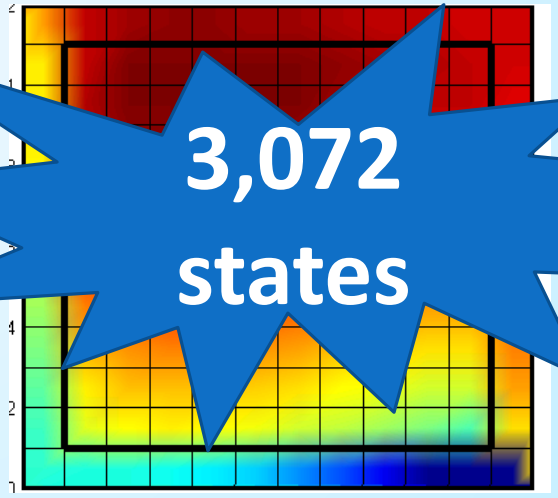
**5x5**

**Fuel Direction**



**10x10**

Air Direction



**3,072 states**

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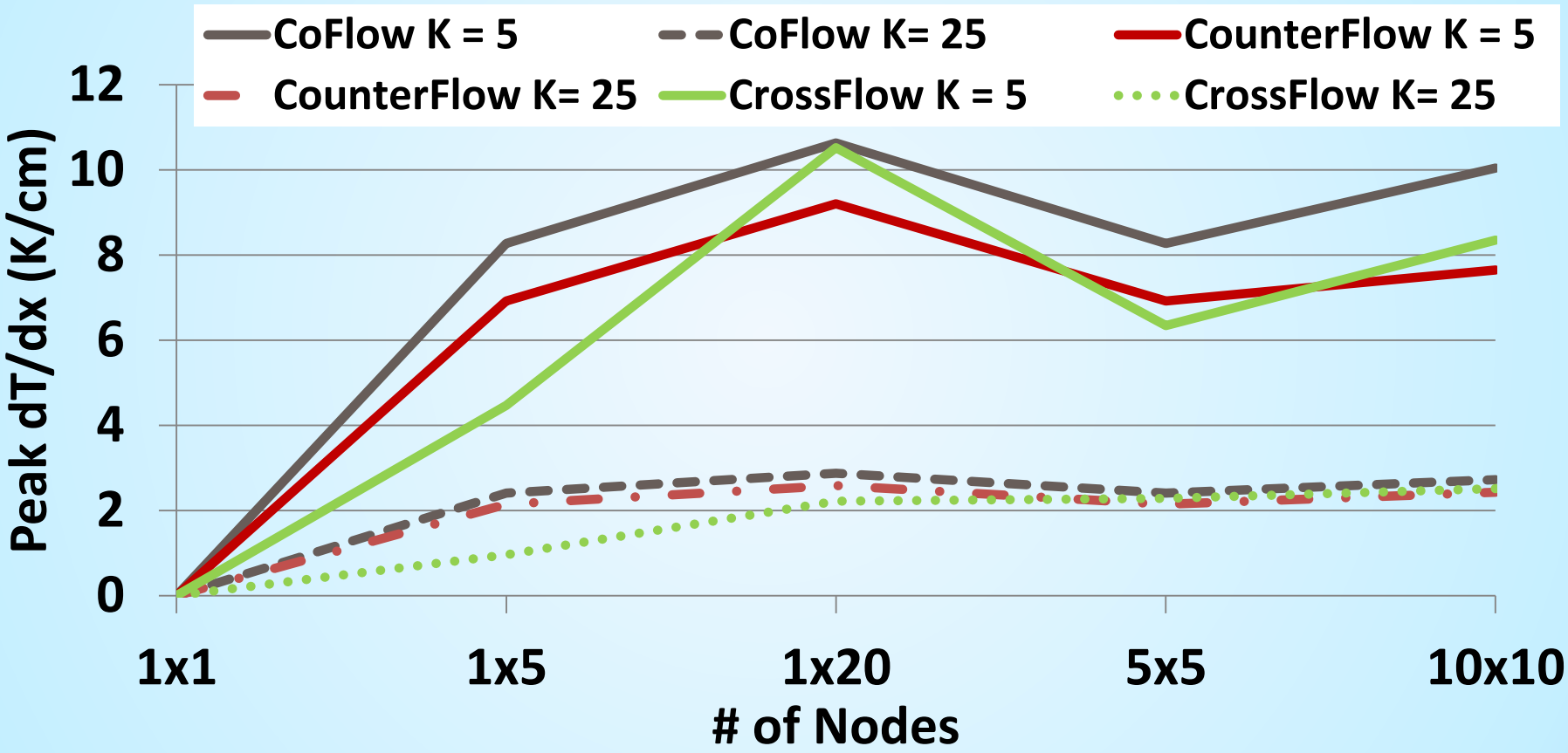
# System Level Impact




» Peak electrolyte temperature gradient with spatial resolution, flow direction, and thermal conductivity

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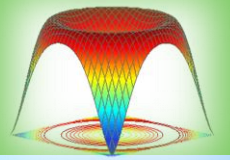
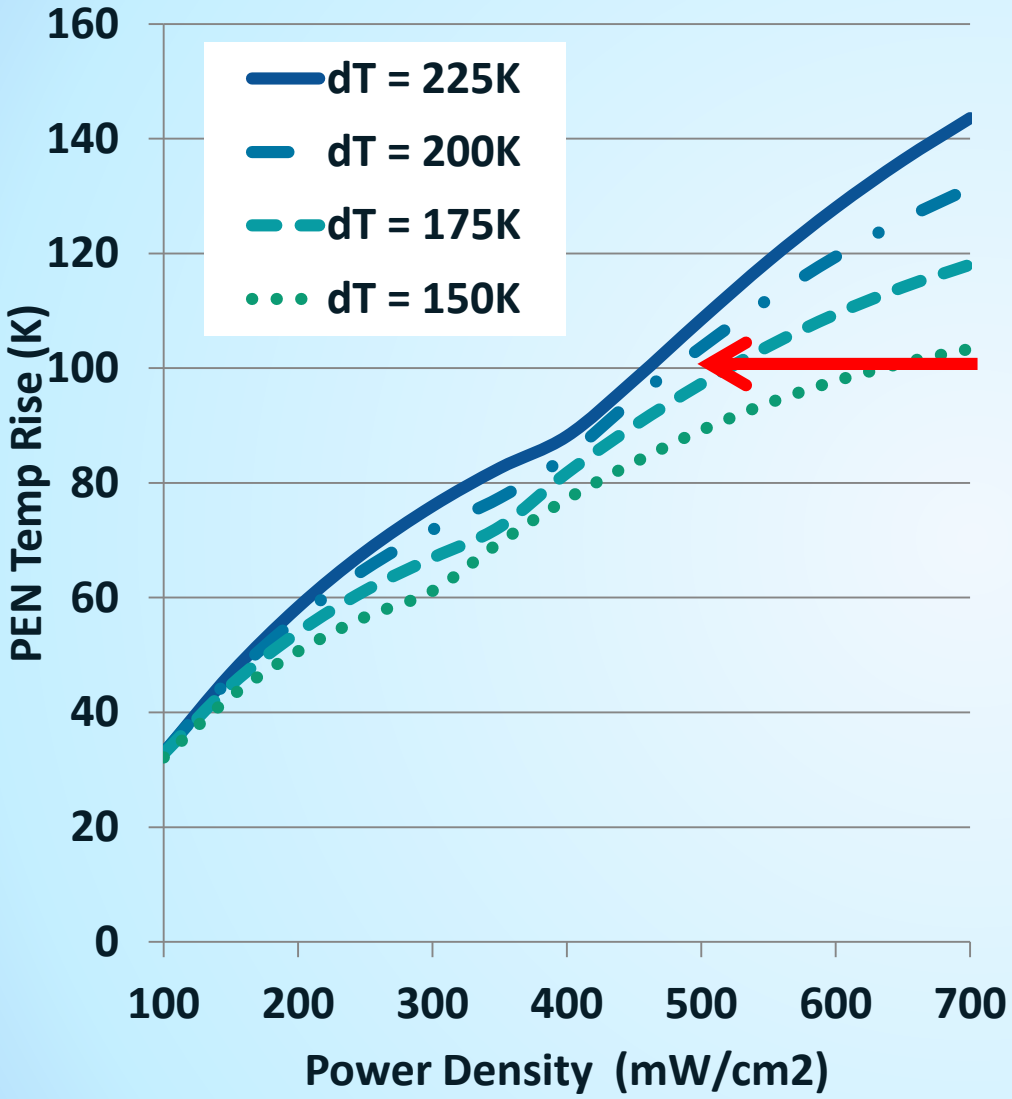
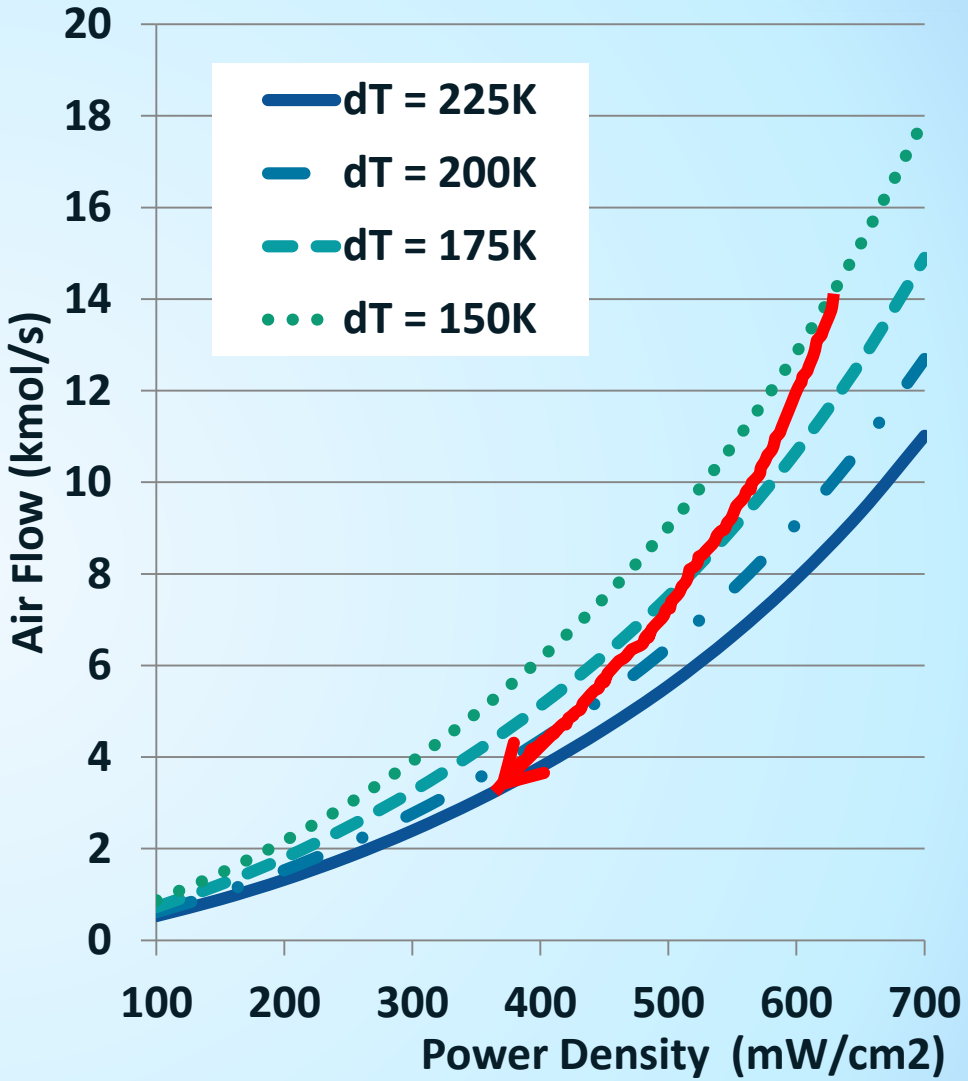
# Edge Heat Transfer






**To maintain temperature gradient, air-flow reduces sharply**

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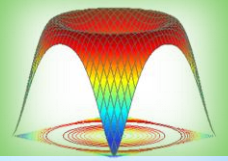
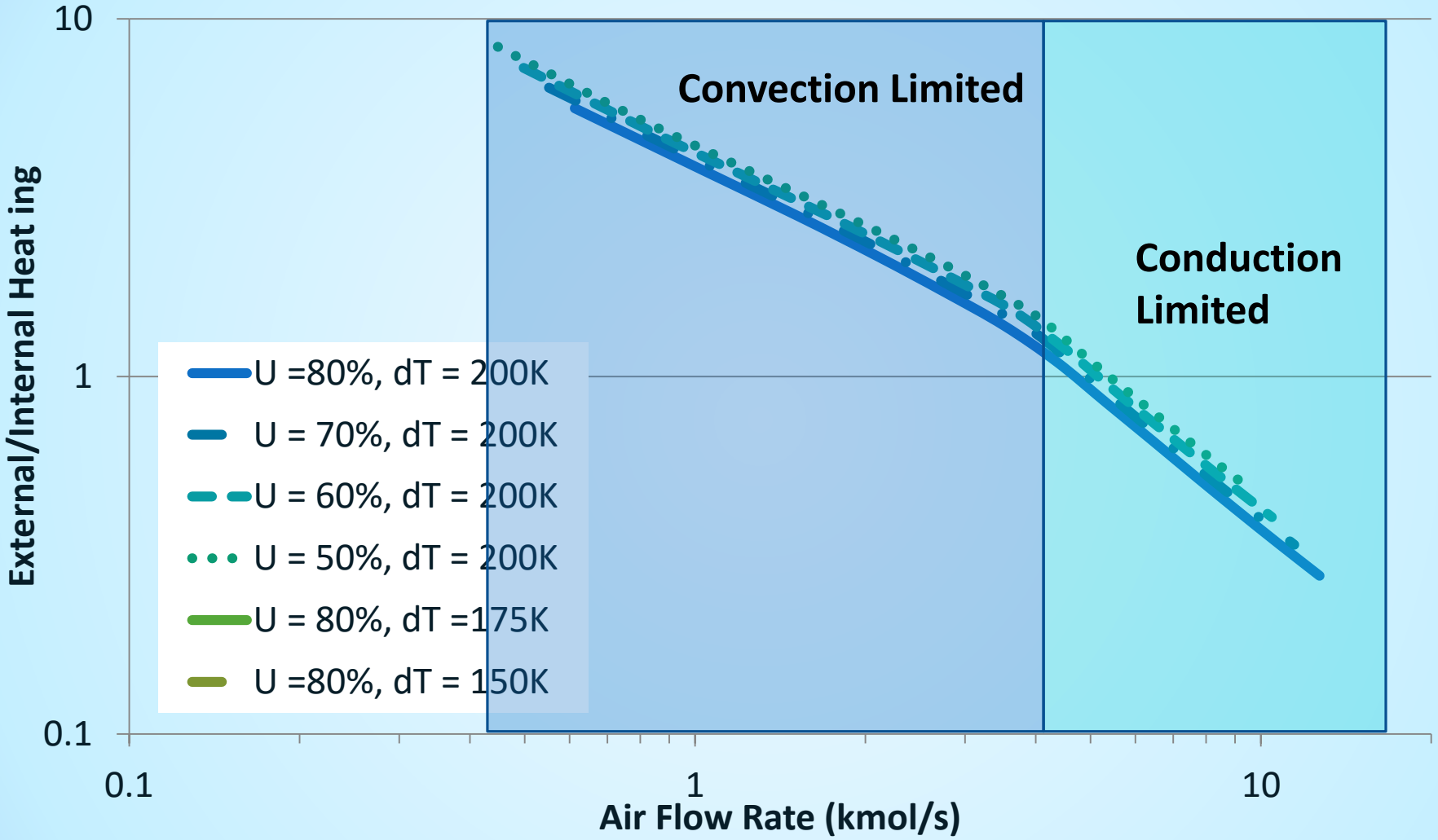
# Edge Heat Transfer



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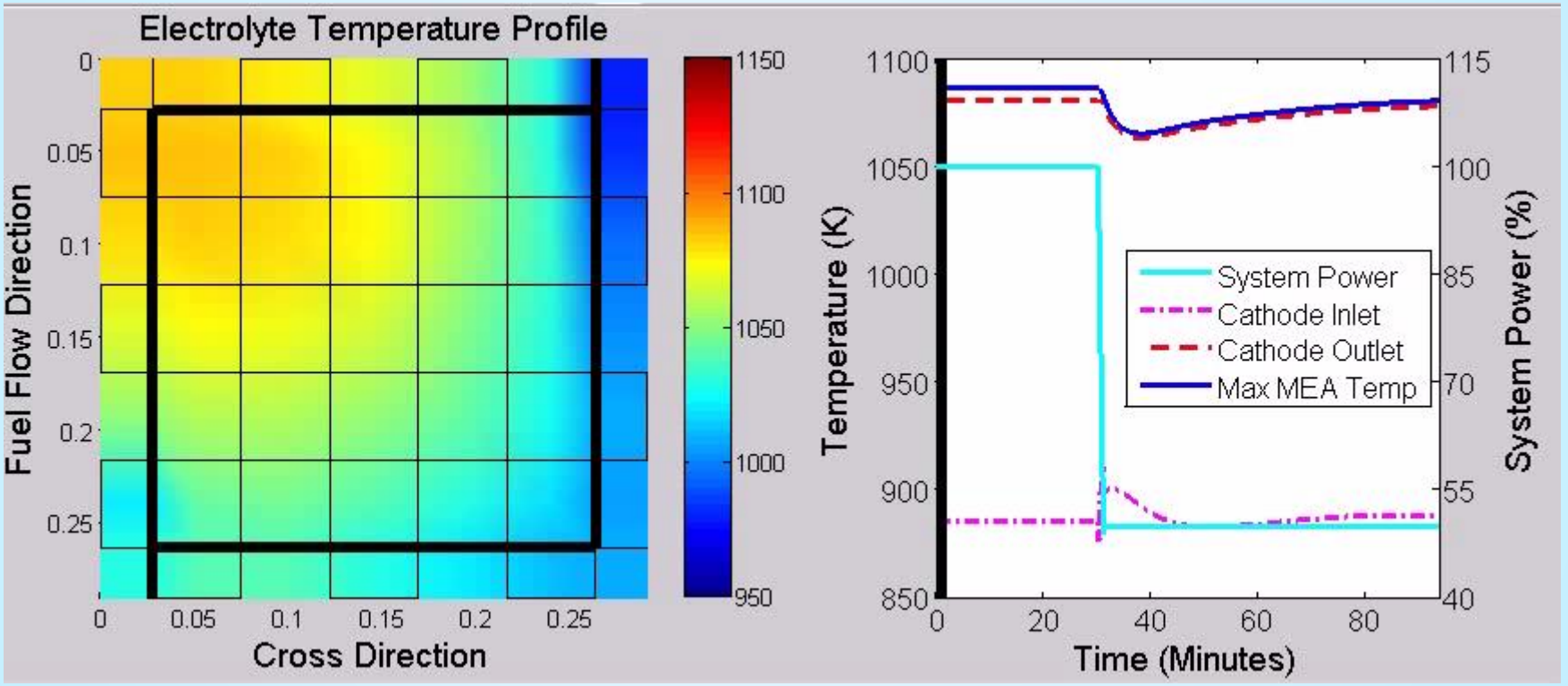
# Edge Heat Transfer




**50% Load shed with feed-forward & feedback control**

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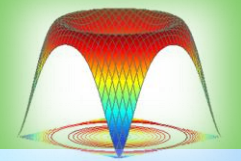
# Turbine Modeling



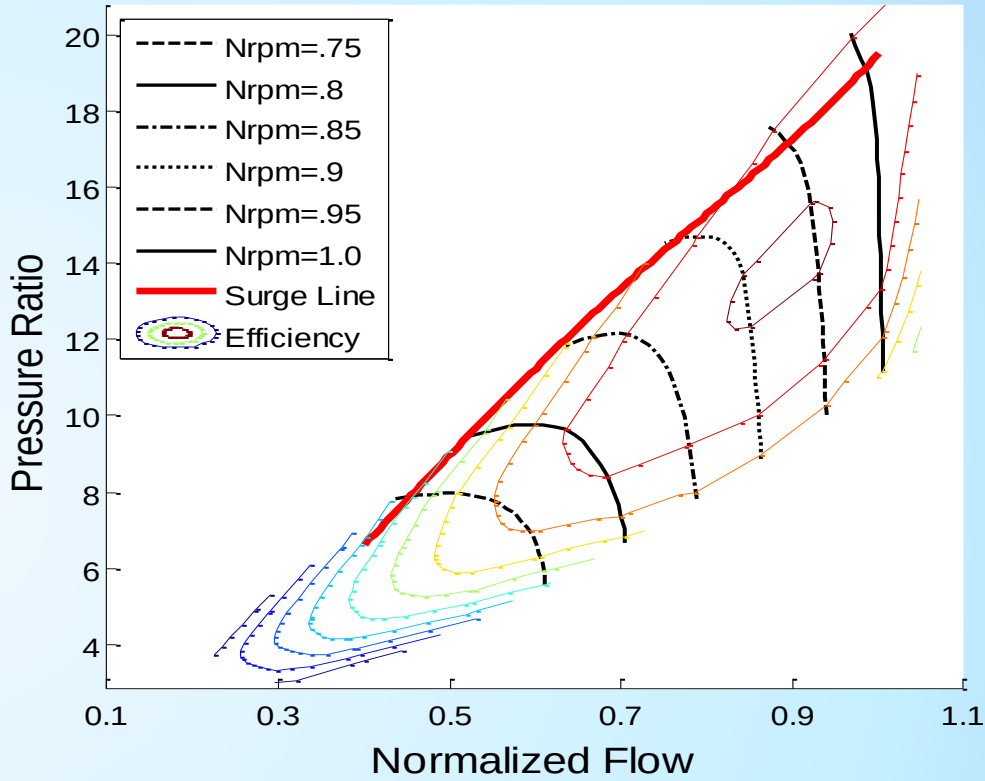
- Pressure – Speed – Flow

$$N_{Flow} = \frac{Flow}{Flow_{des}} \cdot \frac{\sqrt{T_0/T_{des}}}{P_{in}/P_{des}}$$

$$N_{RPM} = RPM\sqrt{T_0/T_{des}} \cdot RPM_{des}$$

- Efficiency
  - Function of speed, PR, and $T_{inlet}$
- Surge Line
- Scaling Pressure

$$PR_{map,new} = 1 + (PR_{des} - 1)\,\frac{PR_{map,orginal} - 1}{PR_{des,original} - 1}$$

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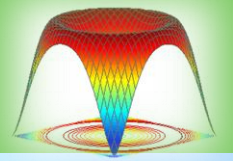
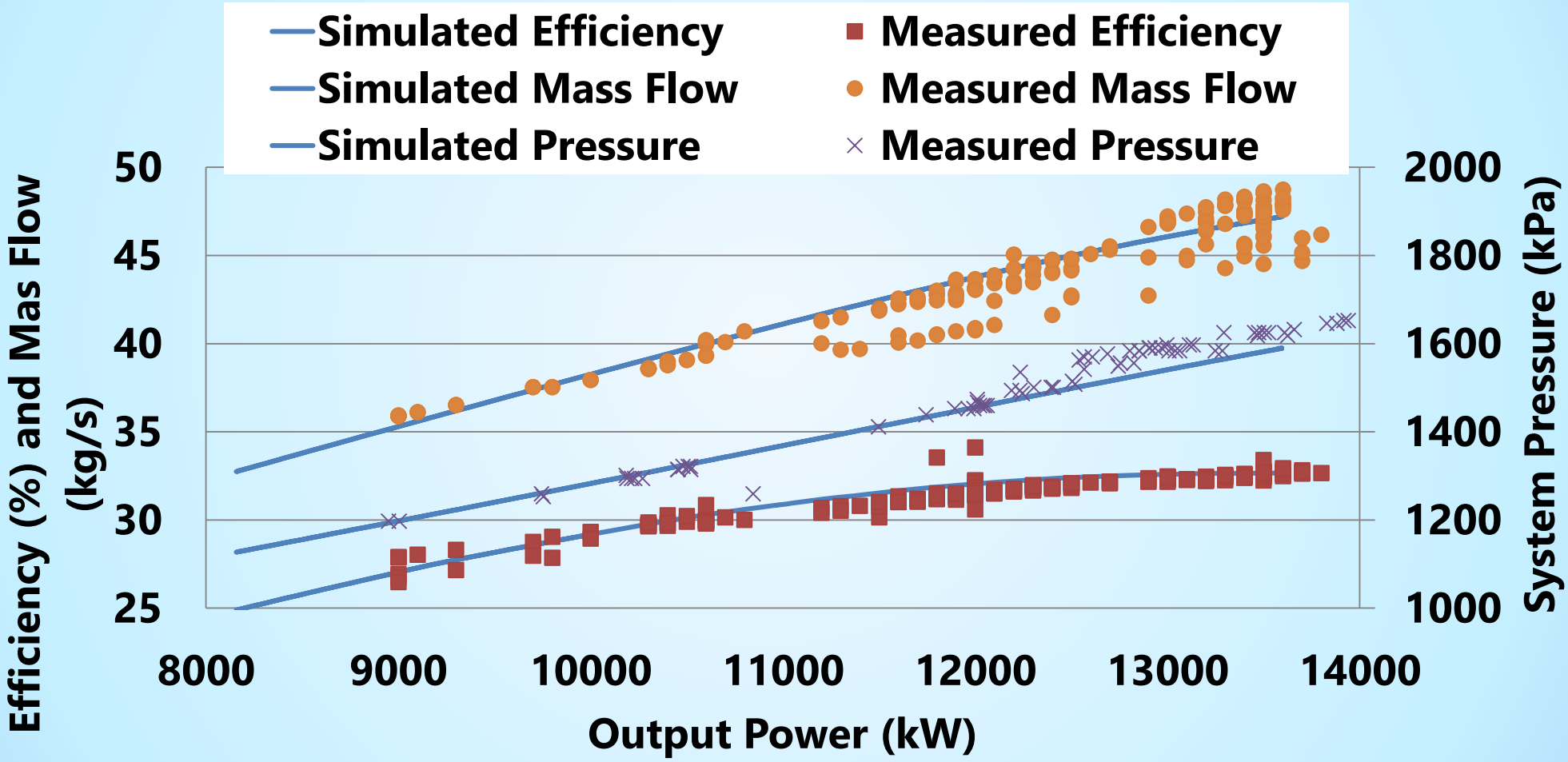
# Verification – axial GT






## Solar Titan-130®

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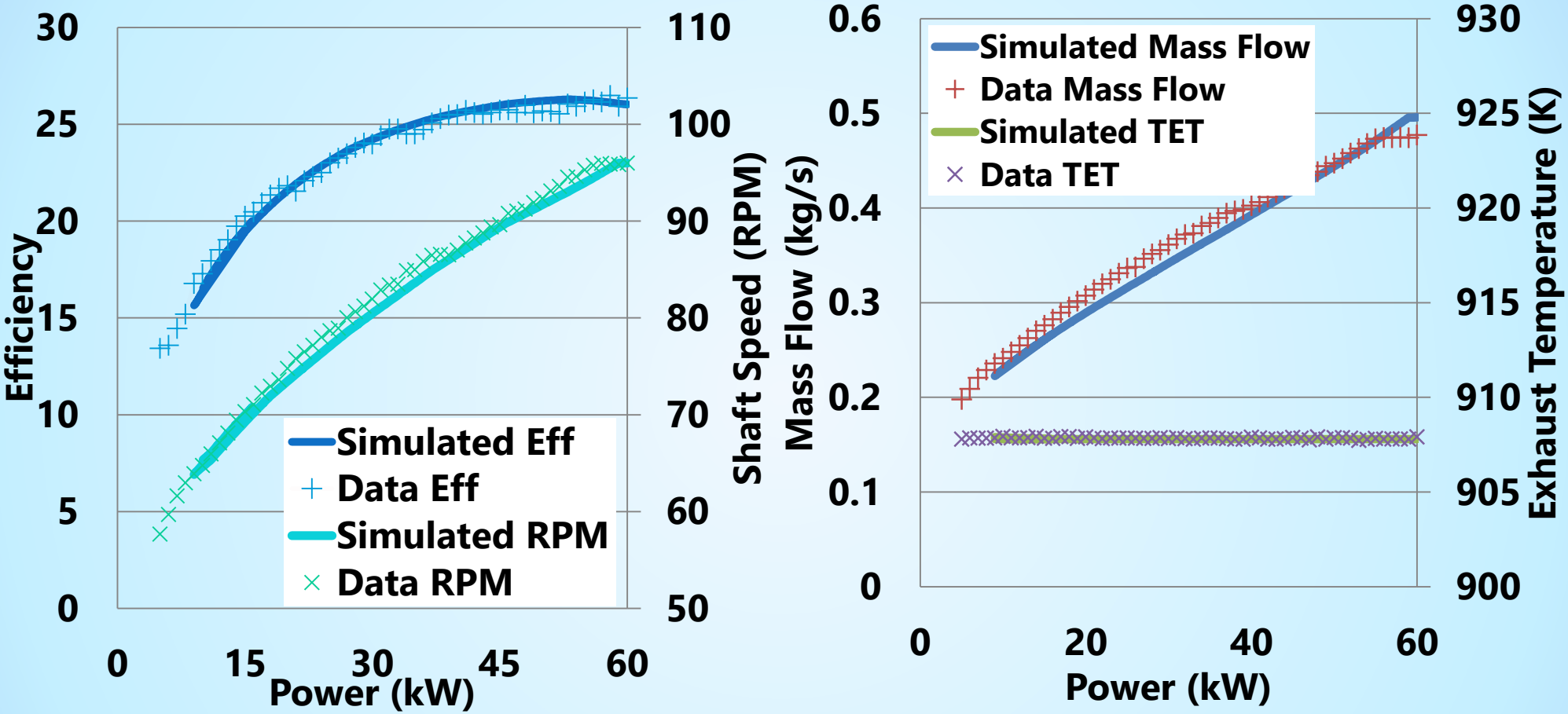
# Verification – mGT




## Capstone C-65®

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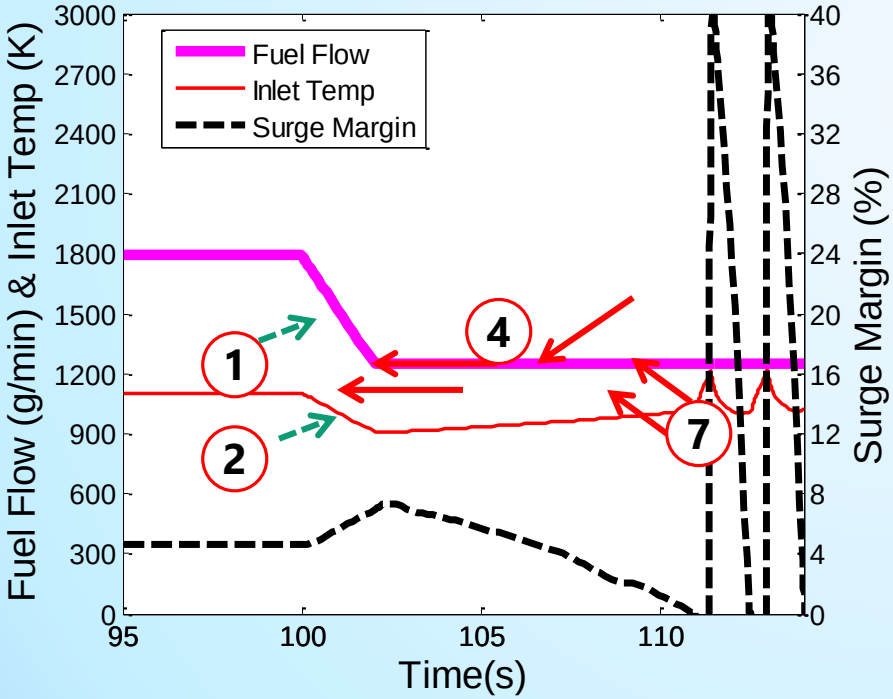
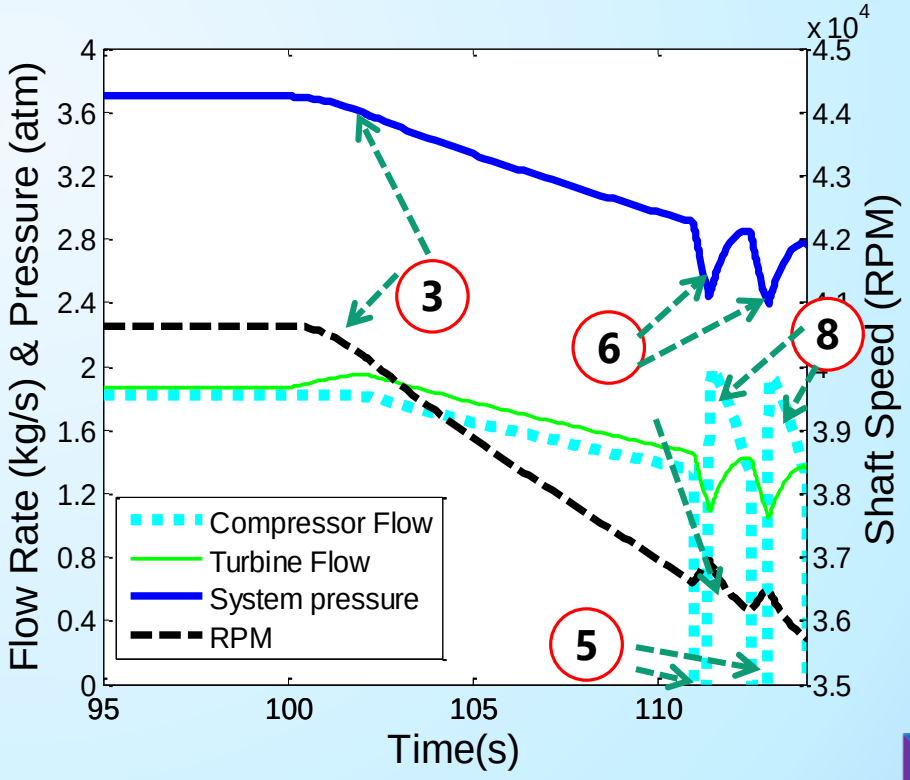
# Stall/Surge –Turn down

1) Fuel input to the combustor is cut off.
2) Turbine inlet temperature/power drops, rotational speed slows
3) Shaft speed reduction occurs faster than the turbine can expel the mas stored in the system to maintain surge margin.
4) **Surge line is reached**
5) Negligible compressor flow and load

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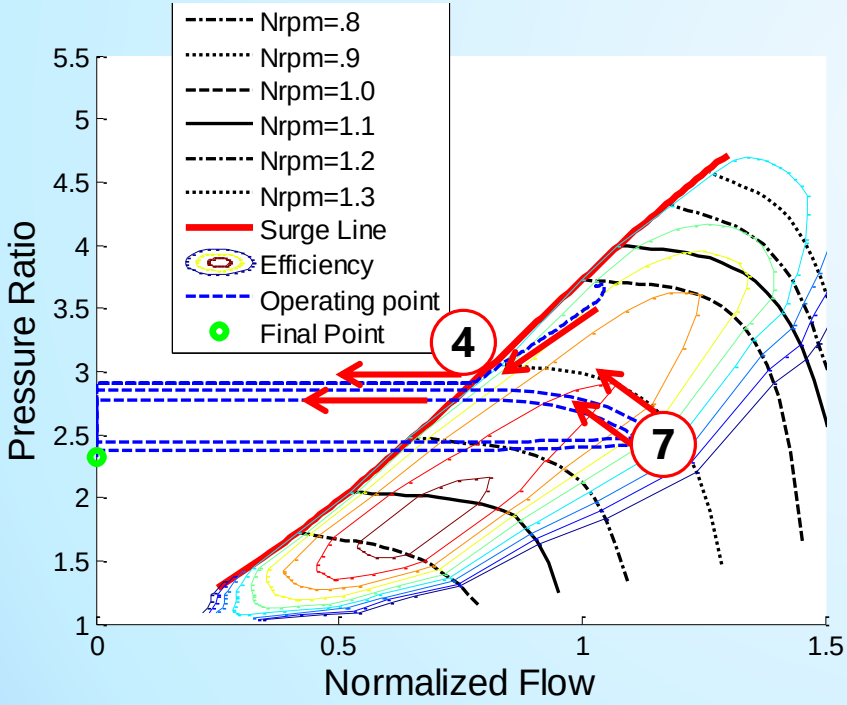
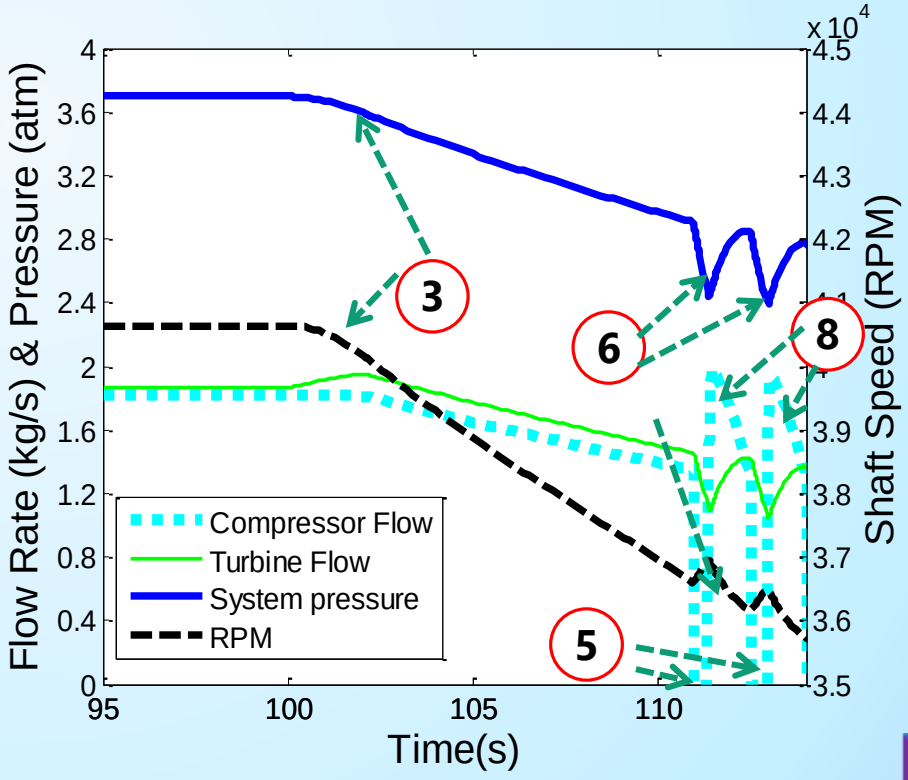
# Stall/Surge –Turn down

6) Shaft speed increases, pressure drops
7) Surge margin reaches critical level (10-20%), flow re-attaches
8) Compressor mass flow exceeds pre-stall level (high RPM, low press)
9) Pressure climbs along a speed line, compression torque slows shaft
10) Process may repeat itself causing failure.

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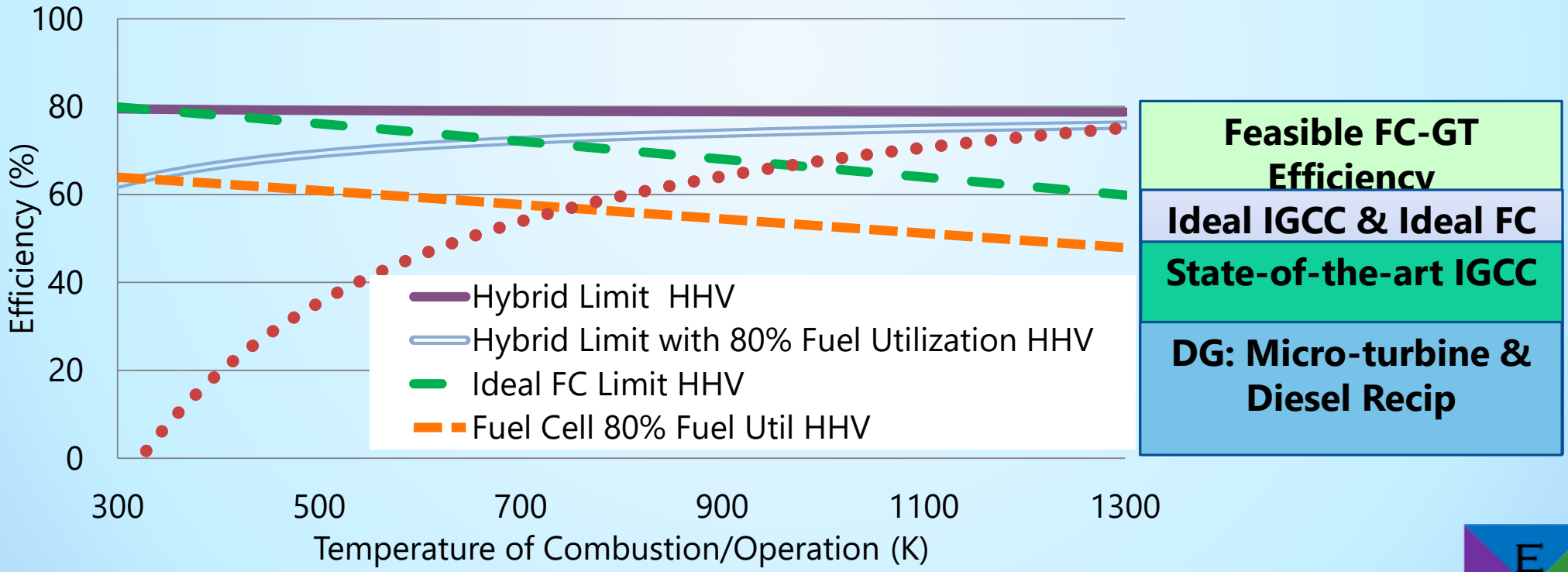
# Theoretical Limits

- FC: Gibbs Energy
  - $\eta_{Fuel\ Cell} = \frac{\Delta G}{\Delta H} = \frac{\Delta H_{LHV} - T_{cell}\Delta S}{\Delta H_{HHV}}$ → → $\frac{\Delta G}{\Delta H} U_{fuel}$
- FC-GT Hybrid:
  - $\eta_{hybrid} = \frac{\Delta G}{\Delta H} + (T_{cell}\Delta S)\frac{T_{hot} - T_{cold}}{T_{hot}}\left(\frac{1}{\Delta H}\right)$
  - $\eta_{hybrid} = \frac{\Delta G + T_{hot}\Delta S - T_{cold} * \Delta S}{\Delta H} = \frac{\Delta H - T_{cold} * \Delta S}{\Delta H} \approx \frac{\Delta G T_{cold}}{\Delta H}$
  - $\eta_{hybrid} = \frac{\Delta G}{\Delta H} U_{fuel} + \left(T_{cell}\Delta S + (1 - U_{fuel})\frac{\Delta G}{\Delta H}\right)\frac{T_{hot} - T_{cold}}{T_{Hot}}$

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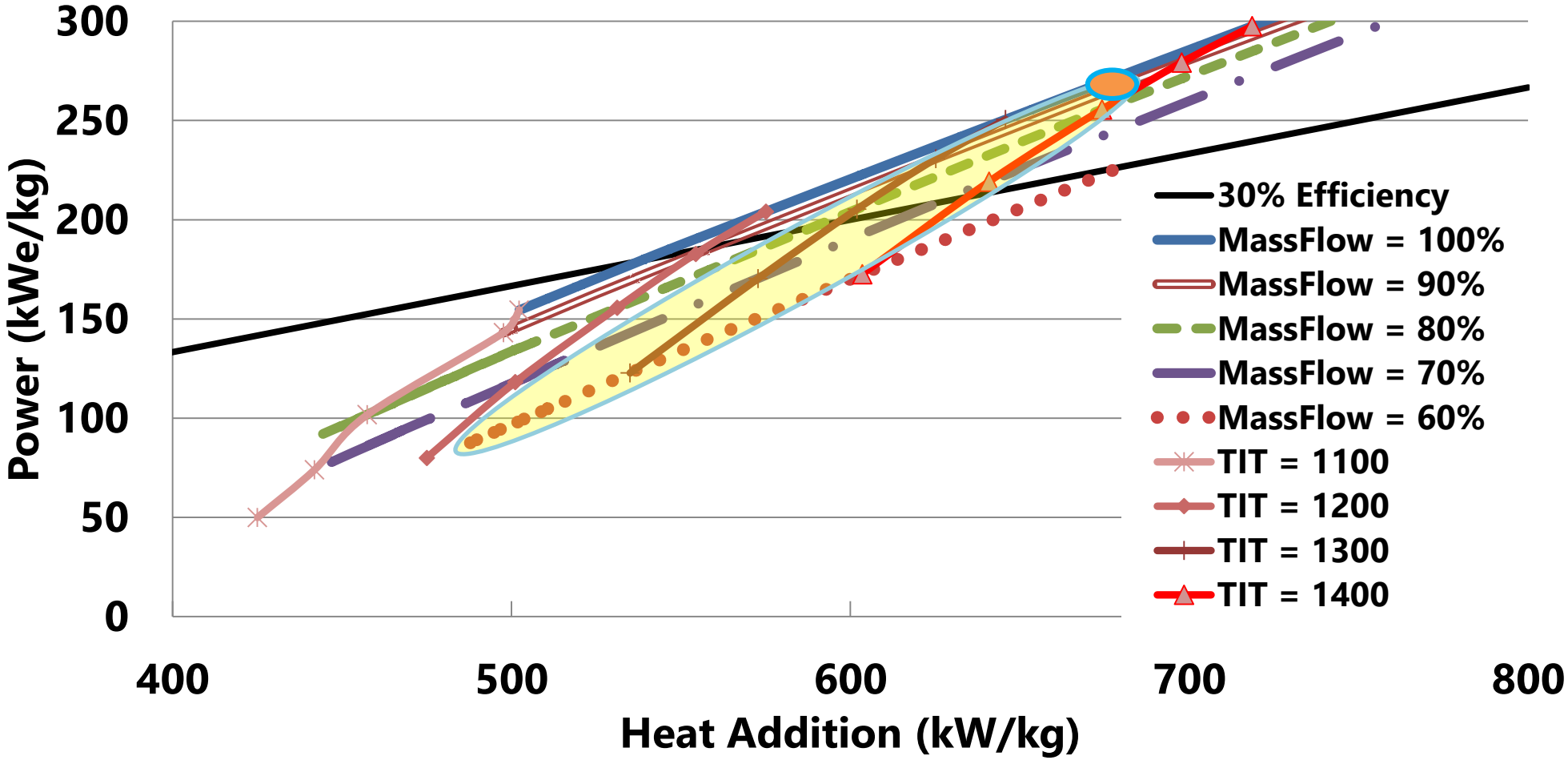
# Simple-Cycle GT




**Axial flow turbine with heat recovery**

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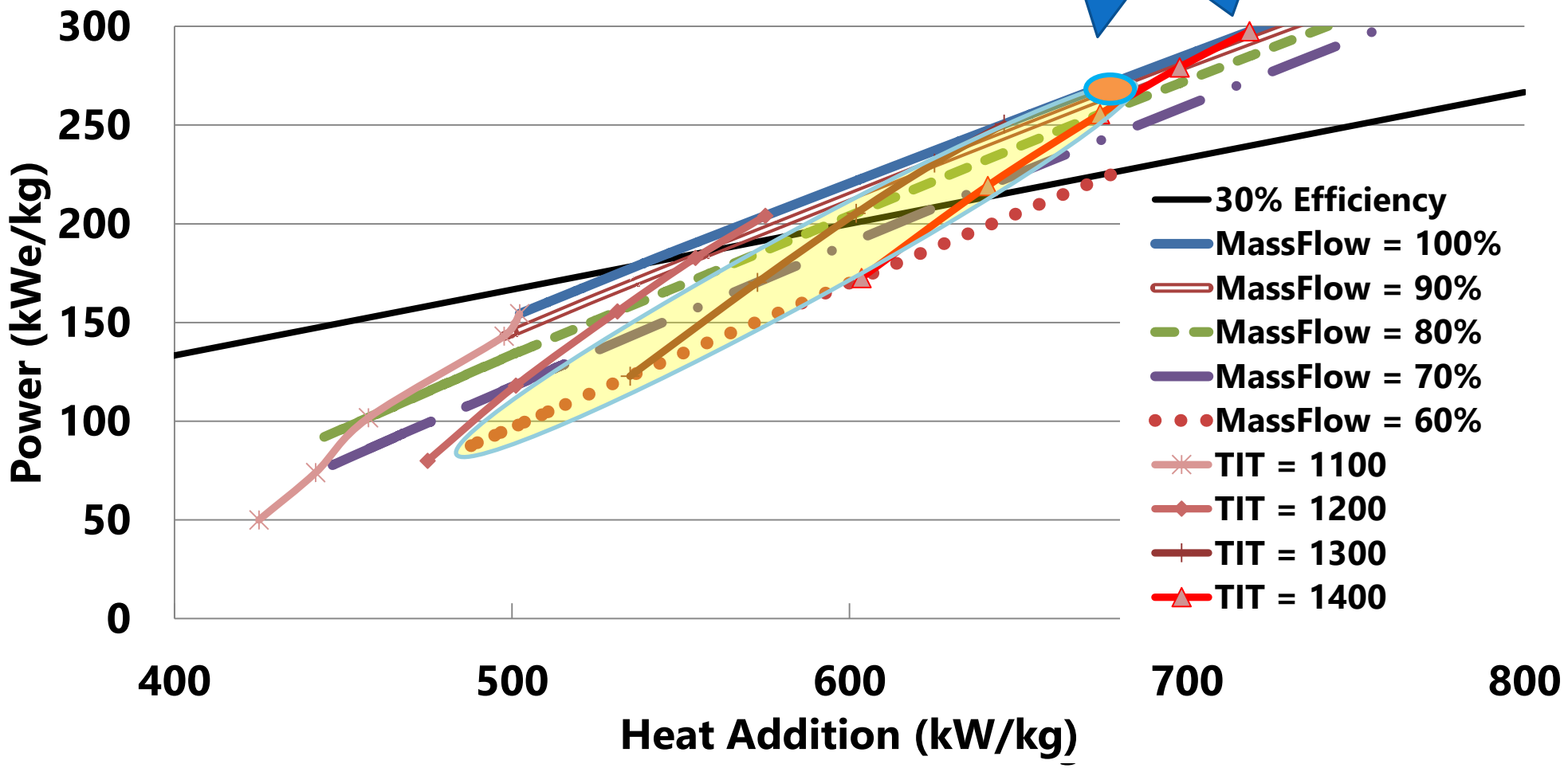
# FC-GT Topping

$$\eta_{hybrid} = \frac{\dot{w}_{FC} + \dot{w}_{MGT}}{\dot{w}_{FC} + \dot{q}_{FC}}$$

**76% (LHV)**
**SOFC-GT**

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# Recirculation

» Closes a large gap between $Q_{FC}$ and $Q_{turb}$

$$q_{GT} = \frac{1}{(1-r)} q_{FC}$$ Only if $q_{GT} > q_{FC}$ since $r \geq 0$

» Changes hybrid performance estimate

$$\eta_{hybrid} = \frac{\dot{w}_{FC} + \dot{w}_{MGT}}{\dot{w}_{FC} + \dot{q}_{FC}} \Rightarrow \frac{\dot{w}_{FC} + (1-r)\dot{w}_{MGT}}{\dot{w}_{FC} + \dot{q}_{FC}}$$

» And estimate of achievable turbine inlet temp (K)

$$T_{turbine\ inlet} = \frac{1}{(1-r)} (T_{oxidizer} - T_{cathode}) + T_{cathode}$$

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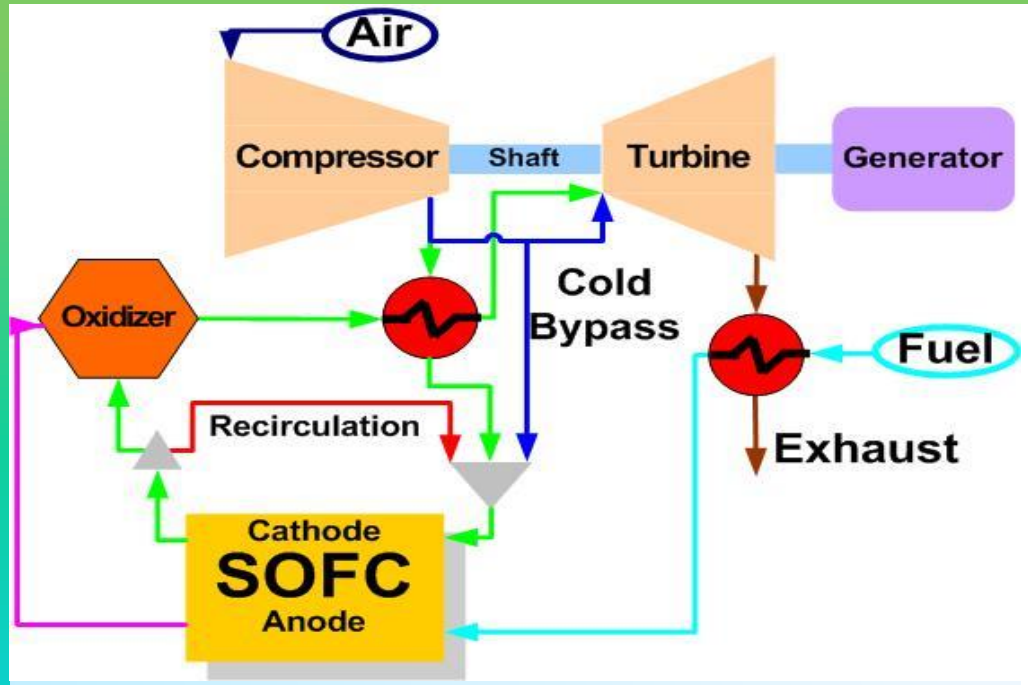
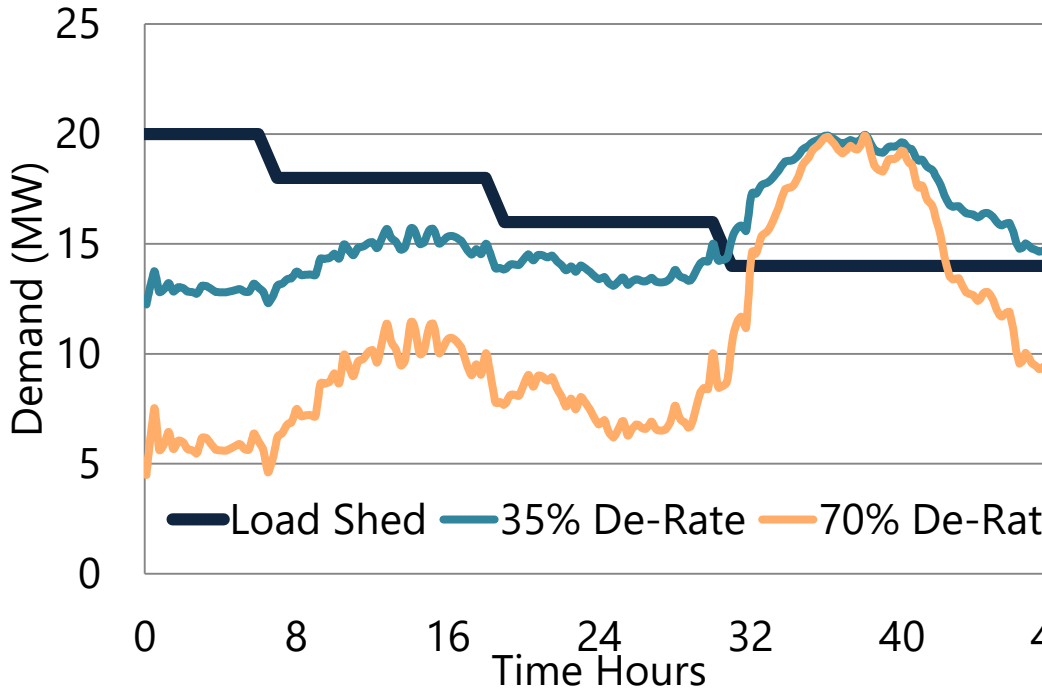
# SOFC-GT Topping




| Control Method | η @ 70% load | η ,48 hr 35% shed | η ,48 hr 70% shed |
|---|---|---|---|
| Pre-FC fuel | 62.4 | 65.3 | N/A |
| Post-FC Fuel | 65.4 | 67.4 | N/A |
| Guide Vane | 72.1 | 72.4 | N/A |
| FC Bypass | 71.5 | 71.9 | N/A |
| Combined | 72.0 | 71.1 | 67.4 |

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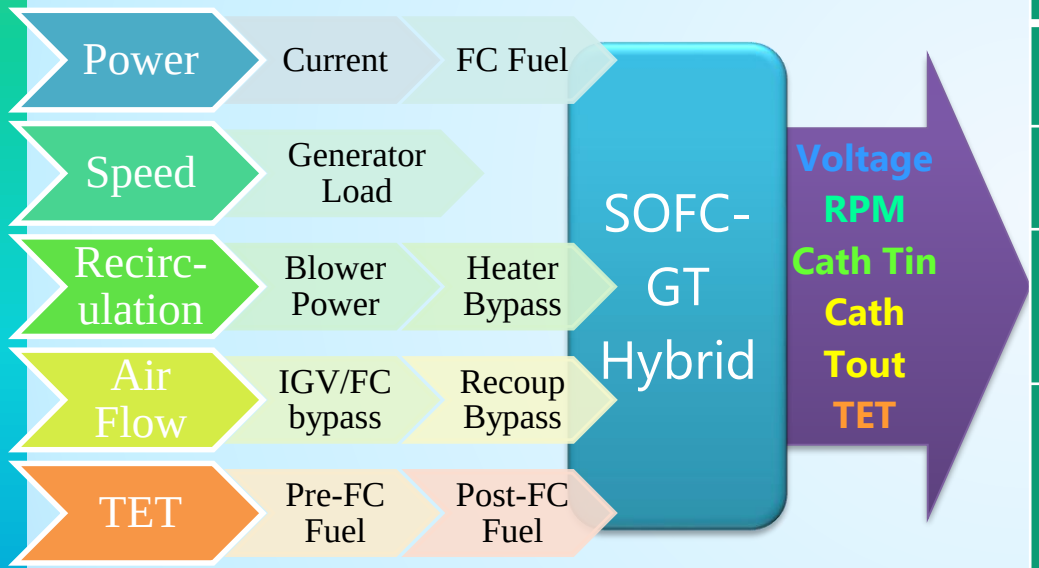
# Control Design

$$FC_By_{FF} = \left(G_{FC_By_FF}\left(1 - \frac{\dot{W}_{demand}}{\dot{W}_{nominal}}\right)\right)^{.813} + FC_By_{initial} - .5\frac{IGV_{FF}}{100}$$

$$IGV_{FF} = \left(G_{IGV_FF}\left(1 - \frac{\dot{W}_{demand}}{\dot{W}_{nominal}}\right)\right)^{3/4} \times 100 + IGV_{initial}$$




| State | Actuator | Integral Gain | Proportional Gain | Feed-forward gain |
|---|---|---|---|---|
| Net Power | Current | 1.0e-2 , 1e-1 | 0.0 | 0.0 |
| Turbine speed | Generator Load | 5.0e-1 | 1.0e2 | 0.0 |
| Cathode Inlet Temperature | Blower Power/Heater Bypass | 5.0e-2 | 4.0 | 0.0 |
| Cathode Exhaust Temperature | IGV angle or FC bypass / Recouperator bypass | 0.0 (IGV) 1e-3(FC_By) | 1.0 (IGV) 2.0 (FC_By) | 0.7 (IGV) 1.16 (FC_By) |
| Turbine Exhaust Temperature | Pre-FC fuel or Post-FC fuel | 5.0e-2 (Pre-) 1.0e-4 (Post) | 0.0 | 0.0 |

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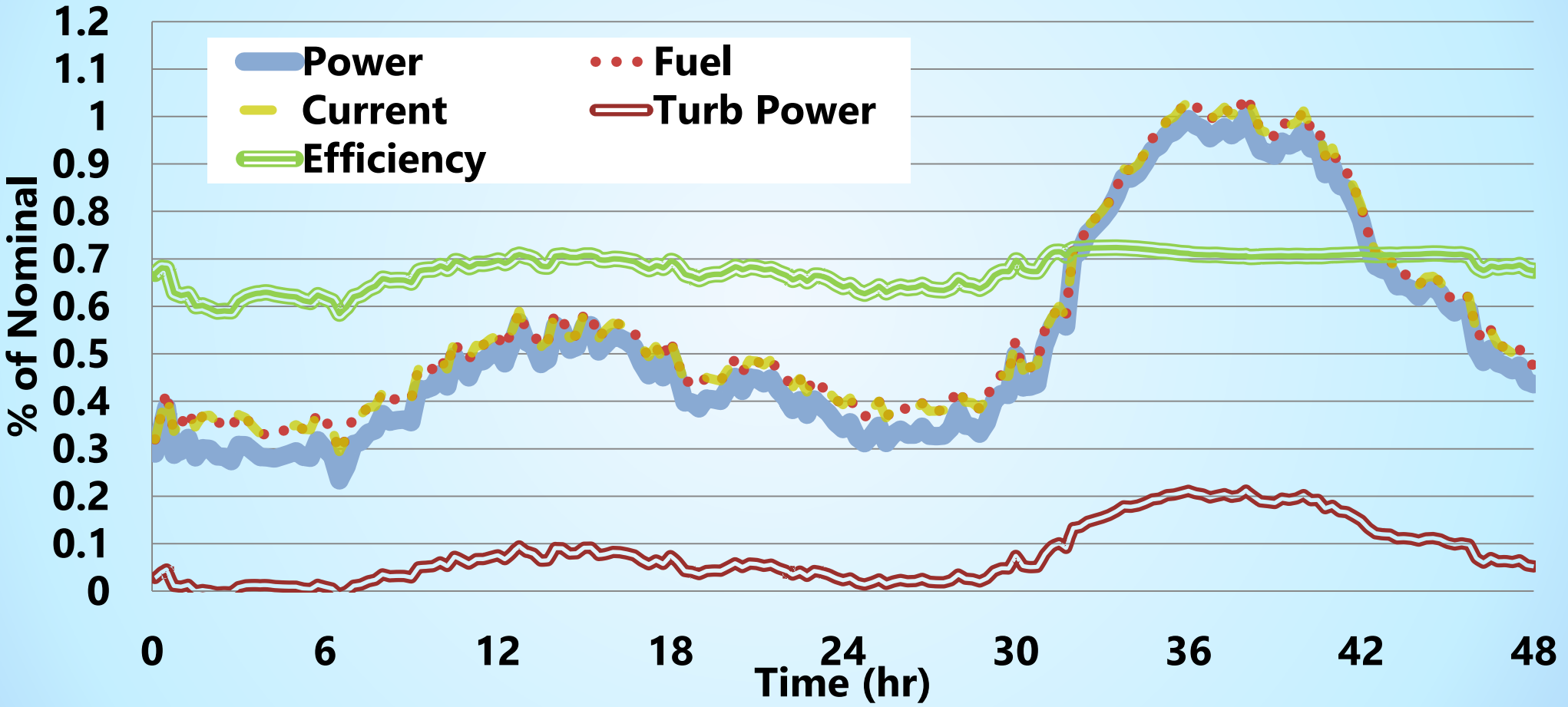
# Load Following

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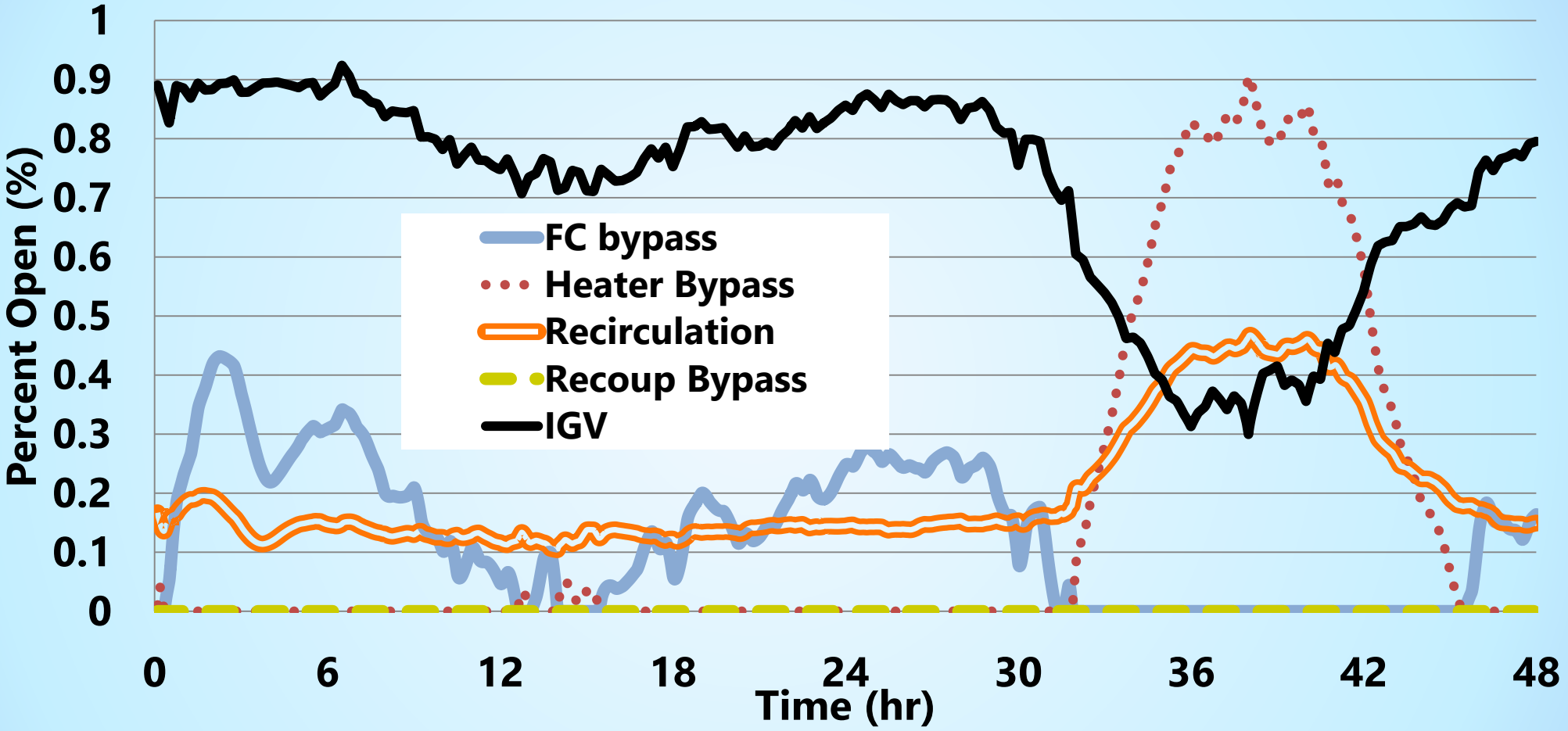


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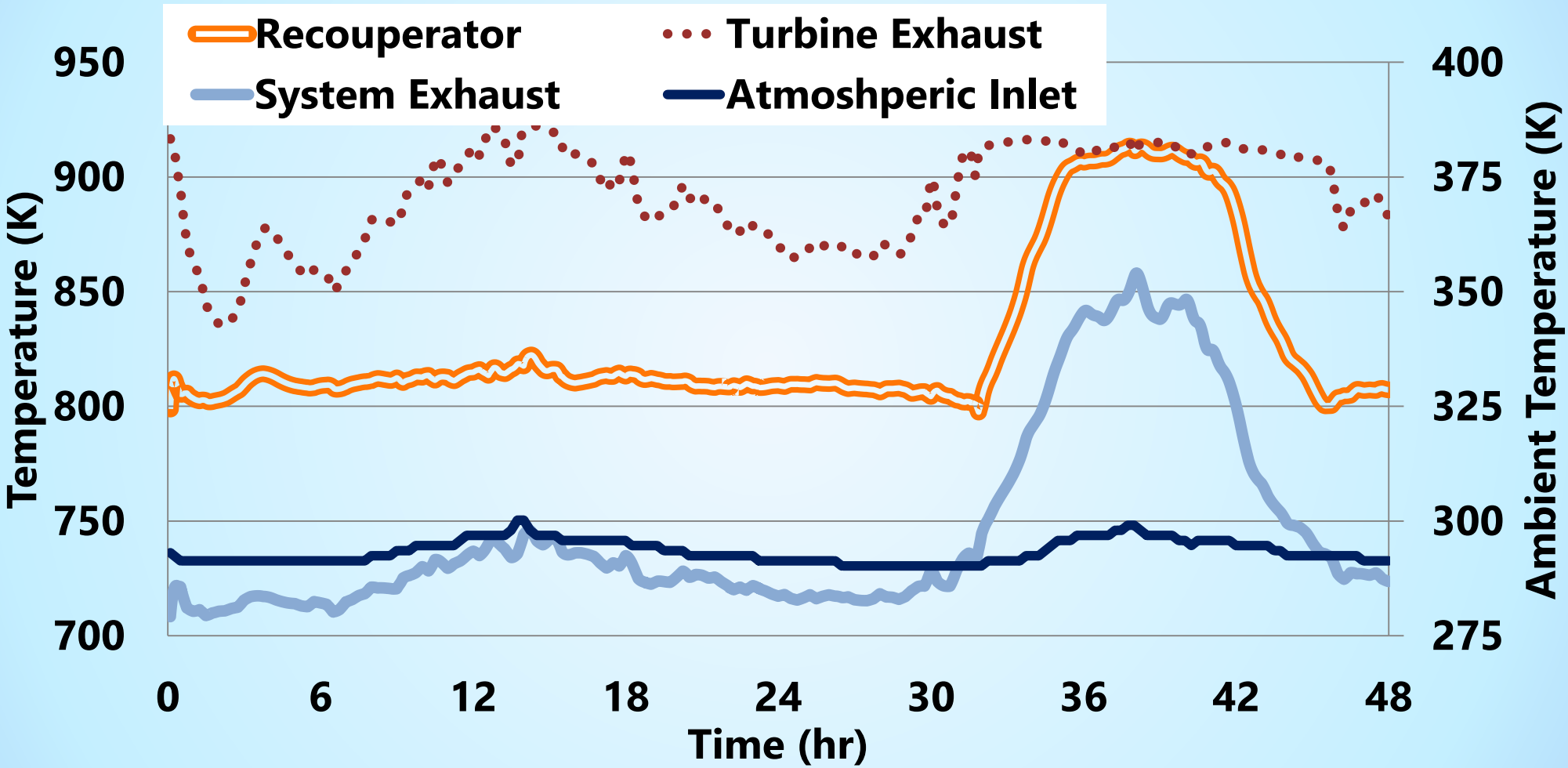


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# Conclusions

- Physical Modeling
  - Spatial resolution of 10 nodes in the primary air flow direction is sufficient
  - Compressor stall/surge can be avoided/recovered by minimizing/expelling mass stored between compressor and turbine
- FC-GT design/control
  - Hybrid system efficiencies can be closely estimated from component performance
  - Existing technology SOFC can achieve 76% (LHV)
  - Turndown to 30% is feasible with ultra-high efficiency and minimal impact on spatial temperature distributions & thermal gradients
  - Speed control, IGV control, and FC bypass control require FF control

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