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# Novel Particle Release Patterns for Increased Receiver Thermal Efficiency

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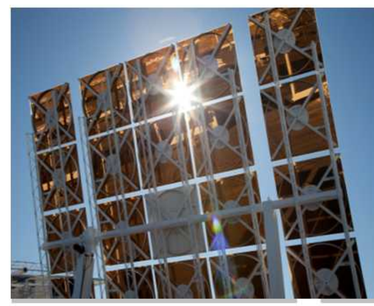

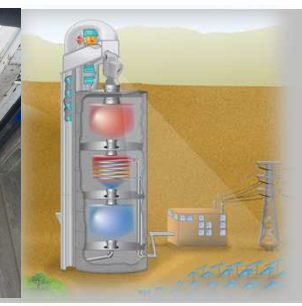


# Overview

- Introduction
- Modeling
- Testing
- Summary

# Need Receivers for Higher Temperature Applications

- Electricity production
  - Supercritical $CO_2$ Brayton Cycles (>700 C)
  - Air Brayton Cycles (>1000 C)
    - Combined cycles
- Thermochemical reactions
  - Redox reactors (>1000 C)
  - Solar fuel production (>1000 C)

→ Particle Receivers

# Particle Receivers - Challenges

- Indirect particle heating
  - Hot spots and flux limitations on walls
  - Heat transfer limitations from walls to particles
  - Significant re-radiation losses from walls at high temperatures
- Direct particle heating
  - Need to improve efficiency of free-falling particle curtains

➡ Employ novel particle release patterns to increase light trapping and increase efficiency at higher particle temperatures

# Objective

- Develop new particle release configurations that increase solar absorptance and thermal efficiency

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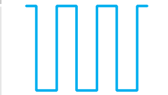
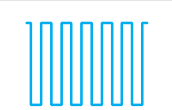
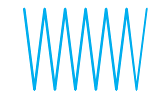
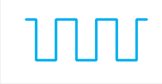
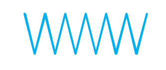
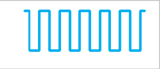
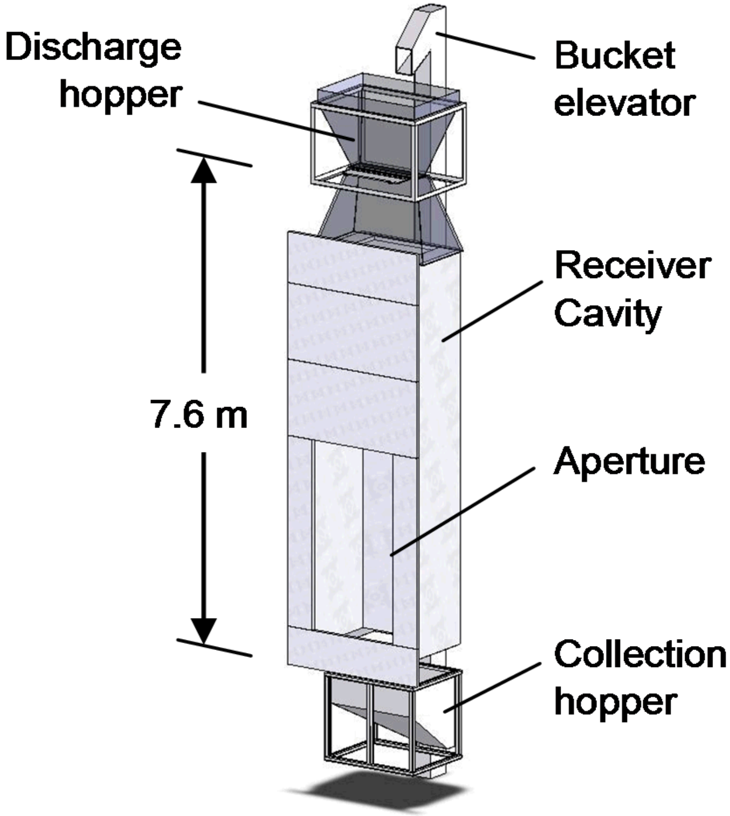
# Evaluate Alternative Particle Release Patterns

| Case | Amplitude (m) | Wavelength (m) | Wave Form | Illustration |
|---|---|---|---|---|
| **Baseline** | N/A | N/A | N/A |  |
| **Case 1** | High (0.4) | High (0.33) | Square |  |
| **Case 2** | High (0.4) | Low (0.17) | Square |  |
| **Case 3** | High (0.4) | Low (0.17) | Triangle |  |
| **Case 4** | High (0.4) | High (0.33) | Triangle |  |
| **Case 5** | Low (0.2) | High (0.33) | Square |  |
| **Case 6** | Low (0.2) | Low (0.17) | Triangle |  |
| **Case 7** | Low (0.2) | High (0.33) | Triangle |  |
| **Case 8** | Low (0.2) | Low (0.17) | Square |  |

# Model Previous On-Sun Tests

(Siegel and Kolb, 2008)

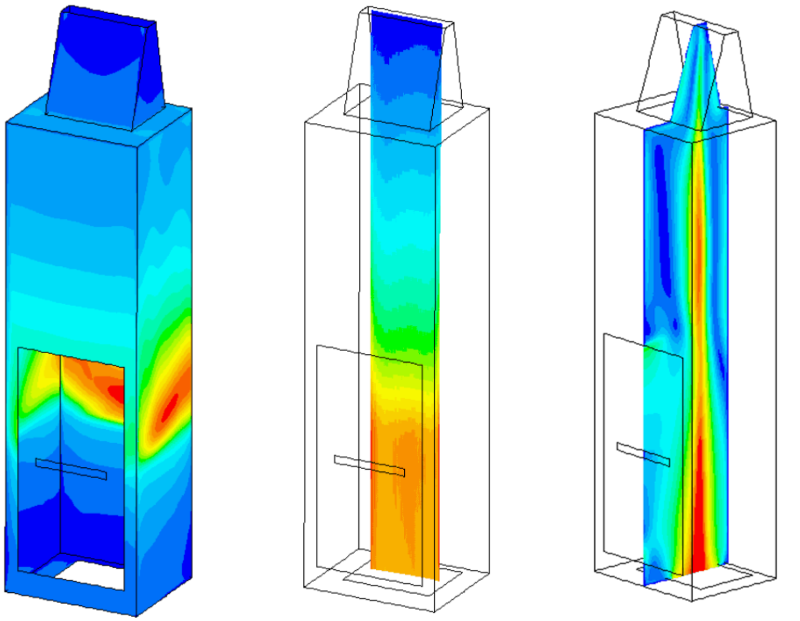
- Nine on-sun tests performed with varying particle mass flow rates (3.8 – 8.7 kg/s-m) and total concentrated thermal input power (1.6 – 2.5 $MW_{th}$)



# Computational Model Validated

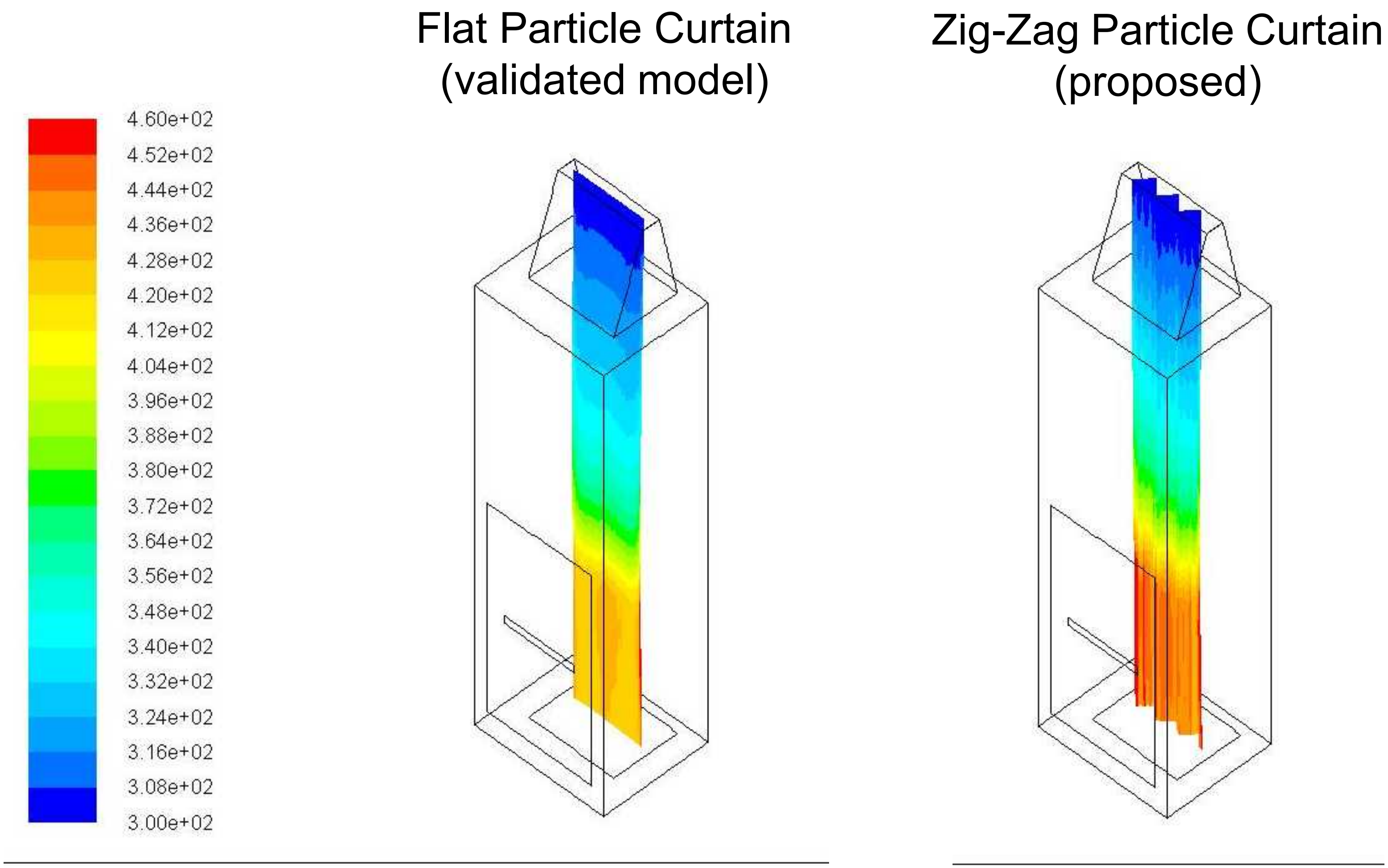
Ho et al. (2009)

- 3-D model in FLUENT
  - Irradiation from heliostat field
  - Two-band reradiation and emission within cavity
  - Discrete-phase particle transport and heat transfer
  - Gas-phase convection and interaction with particles
  - Wall conduction
  - Radiative and convective heat losses



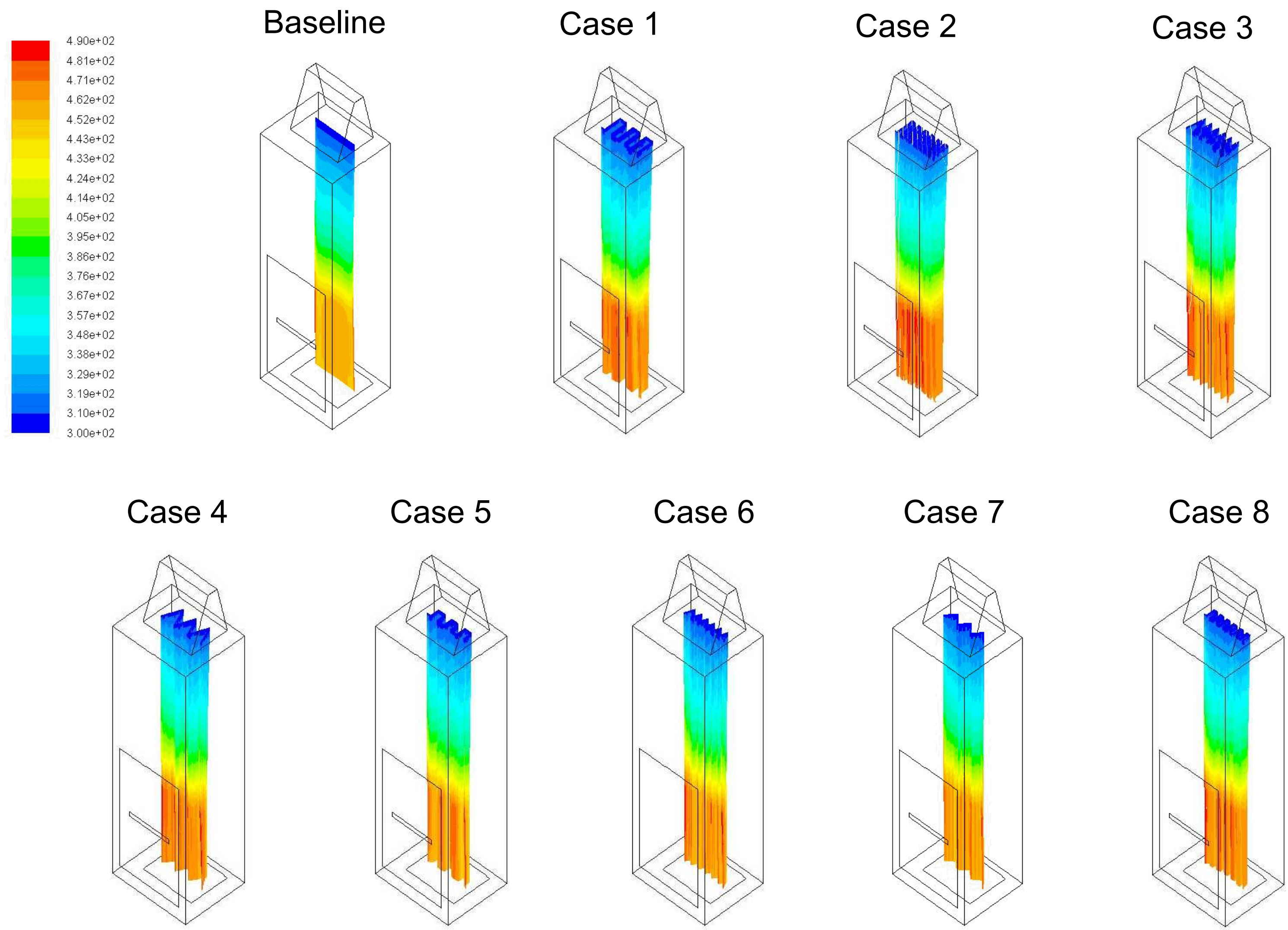
Incident radiation on walls | Particle tracks colored by temperature | Gas flow colored by velocity

# Flat vs. Zig-Zag Particle Curtain

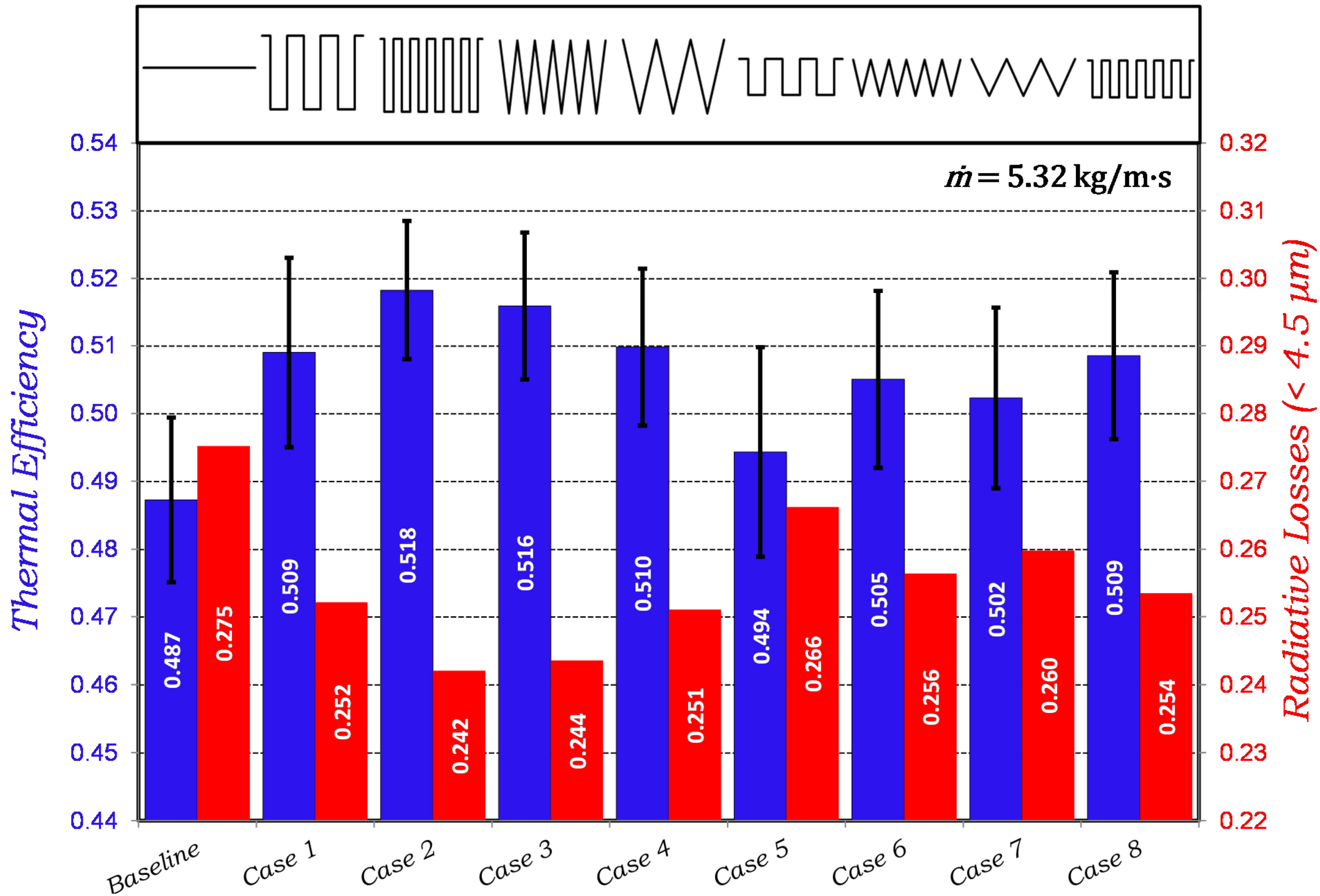



Particle Traces Colored by Particle Temperature (k)

# Results – Particle Temperatures



# Results – Thermal Efficiency

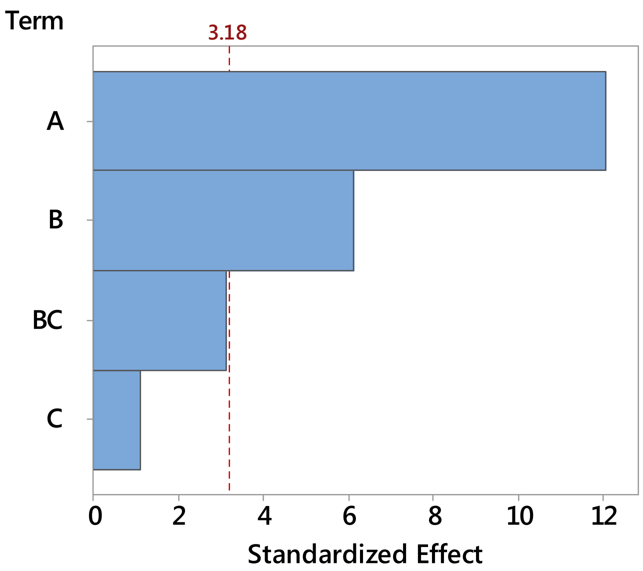





Up to ~7% increase in thermal efficiency over baseline; $T_i$ = 23˚C

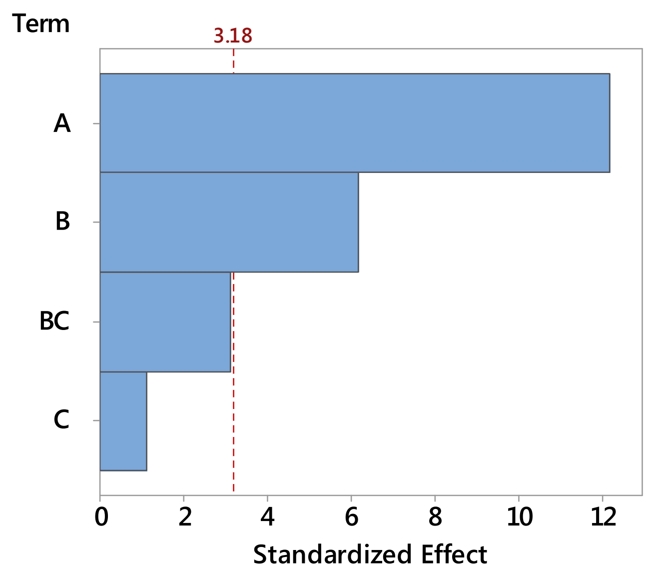
# ANOVA Sensitivity Analysis

Particle Temperature Rise




| Factor | Name |
|---|---|
| A | Amplitude |
| B | Wavelength |
| C | Wave Form |

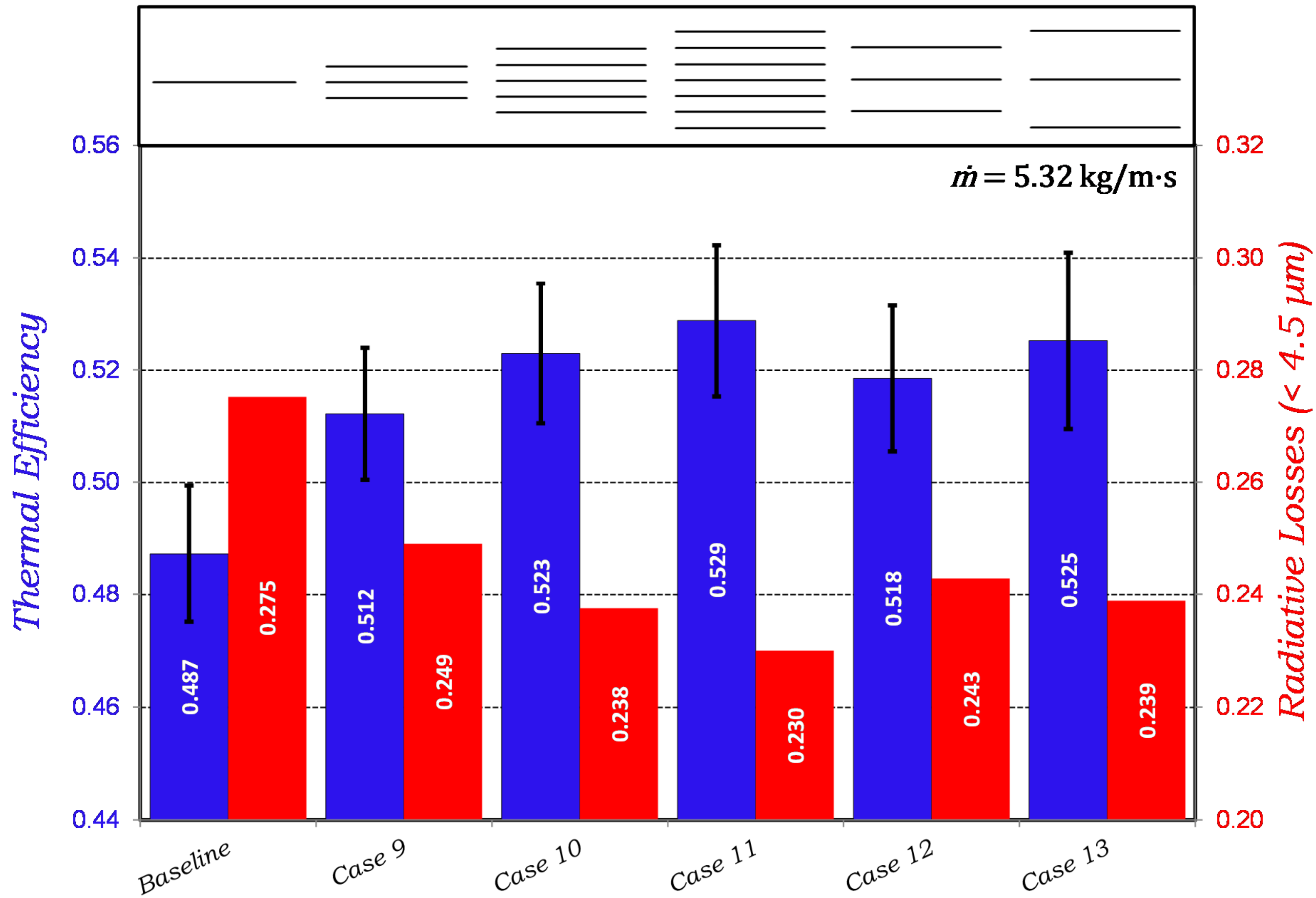
Thermal Efficiency




| Factor | Name |
|---|---|
| A | Amplitude |
| B | Wavelength |
| C | Wave Form |

High amplitude, high frequency (low wavelength) yielded best performance

# Results – Thermal Efficiency






Multiple parallel curtains yield higher efficiencies than baseline (even higher than wave-like patterns)

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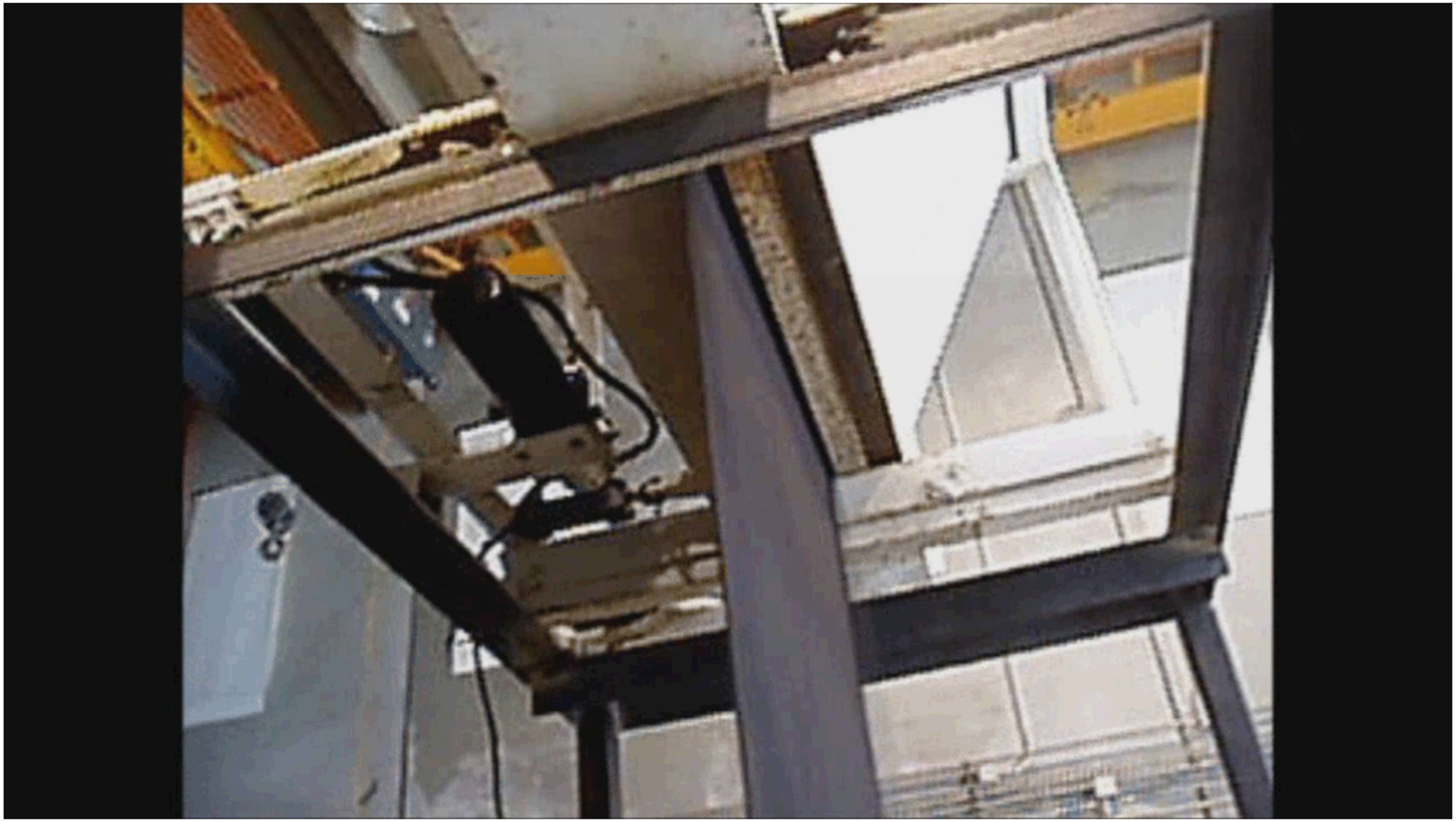
# Test Objectives

- Characterize flow stability and thermal performance of new particle release configurations


# Linear Release



# 16 Particle Release Patterns Tested

# Zig-Zag Release

# Square-Wave Release Pattern

# Parallel-Line Release Pattern

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# Summary

- Simulations indicate particle release patterns (wave-like, parallel lines, mass flow gradients) can increase thermal efficiency of a particle receiver
  - Up to ~7 % at low temperatures (~100-200˚C)
  - Up to ~2-3 % at elevated temperatures (>720˚C)
  - Convective losses become significant at 720˚C
- Testing indicated that novel particle release patterns can be implemented with different discharge slot patterns

# Questions?

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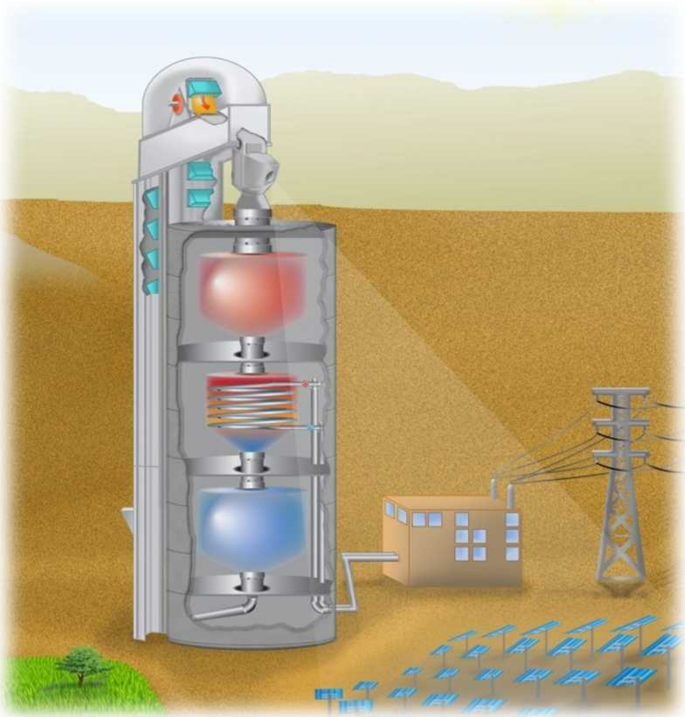

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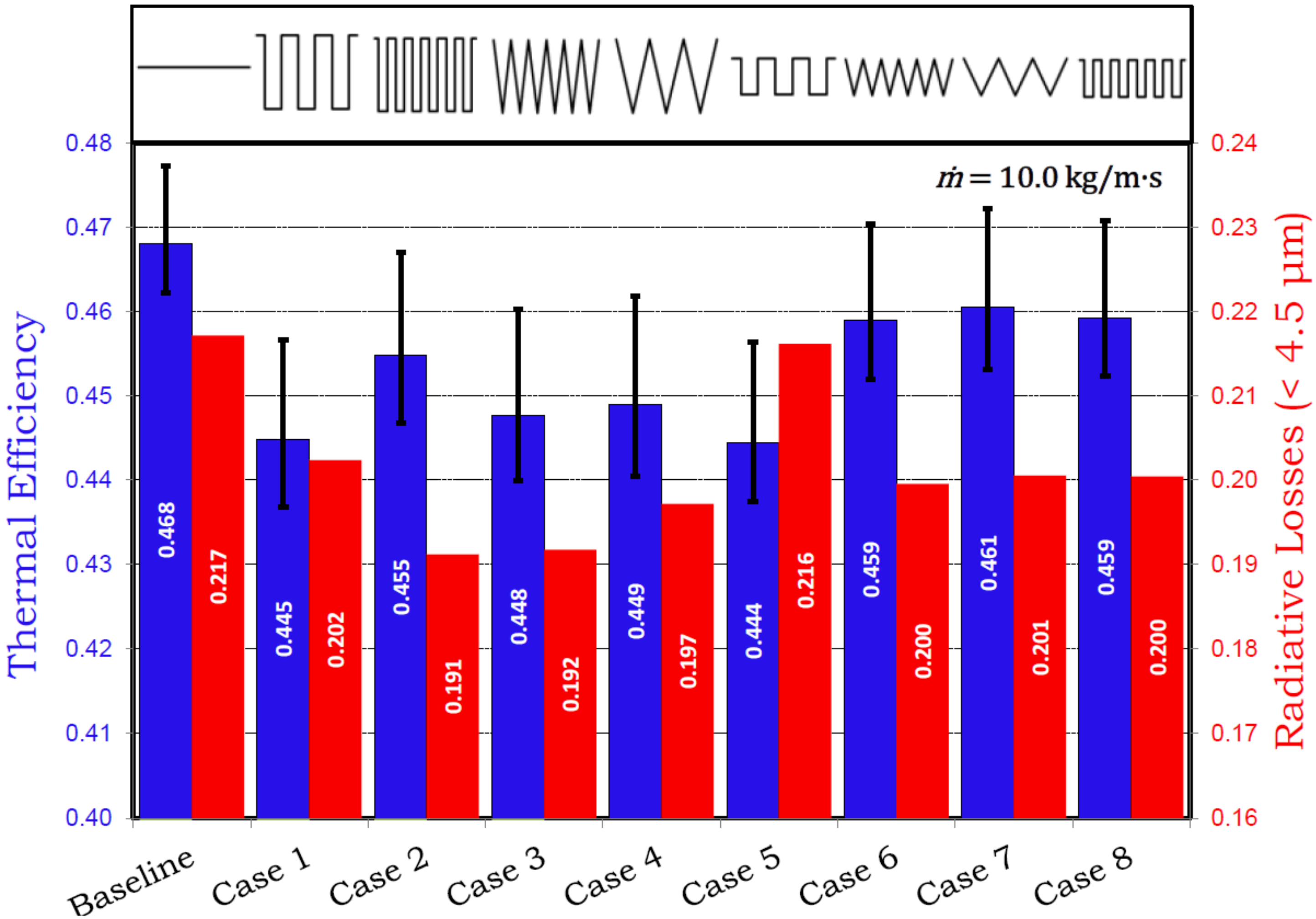
# Backup Slides

# New Release Patterns

| Case | Depth (m) | Scaled Illustration | Case | Depth (m) | Scaled Illustration |
|---|---|---|---|---|---|
| Case 14 | N/A |  | Case 18 | N/A | 12.5 75 12.5 / 0.2 0.6 0.2 |
| Case 15 | N/A |  | Case 19 | N/A | 5 90 5 / 0.2 0.6 0.2 |
| Case 16 | 0.6 |  | Case 20 | N/A | 5 90 5 / 0.1 0.8 0.1 |
| Case 17 | 0.3 |  | Case 21 | N/A | 2.5 10 75 10 2.5 / 0.1 0.1 0.6 0.1 0.1 |

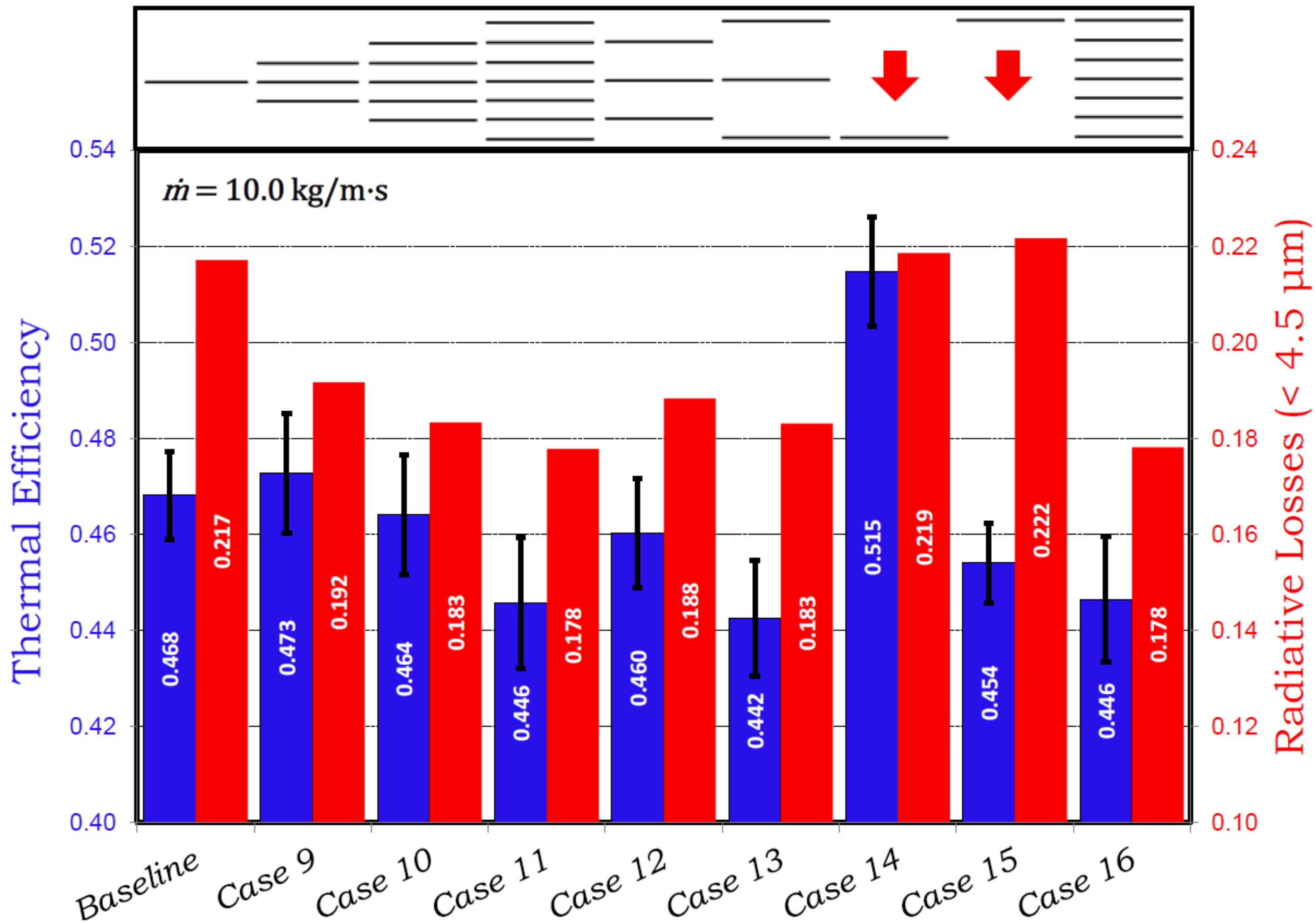
- Red arrow denotes direction of incident flux
- Top numbers indicate percent of mass flow; Bottom numbers indicate length of segment

# Wave-like Efficiency: $T_i$ = 600°C



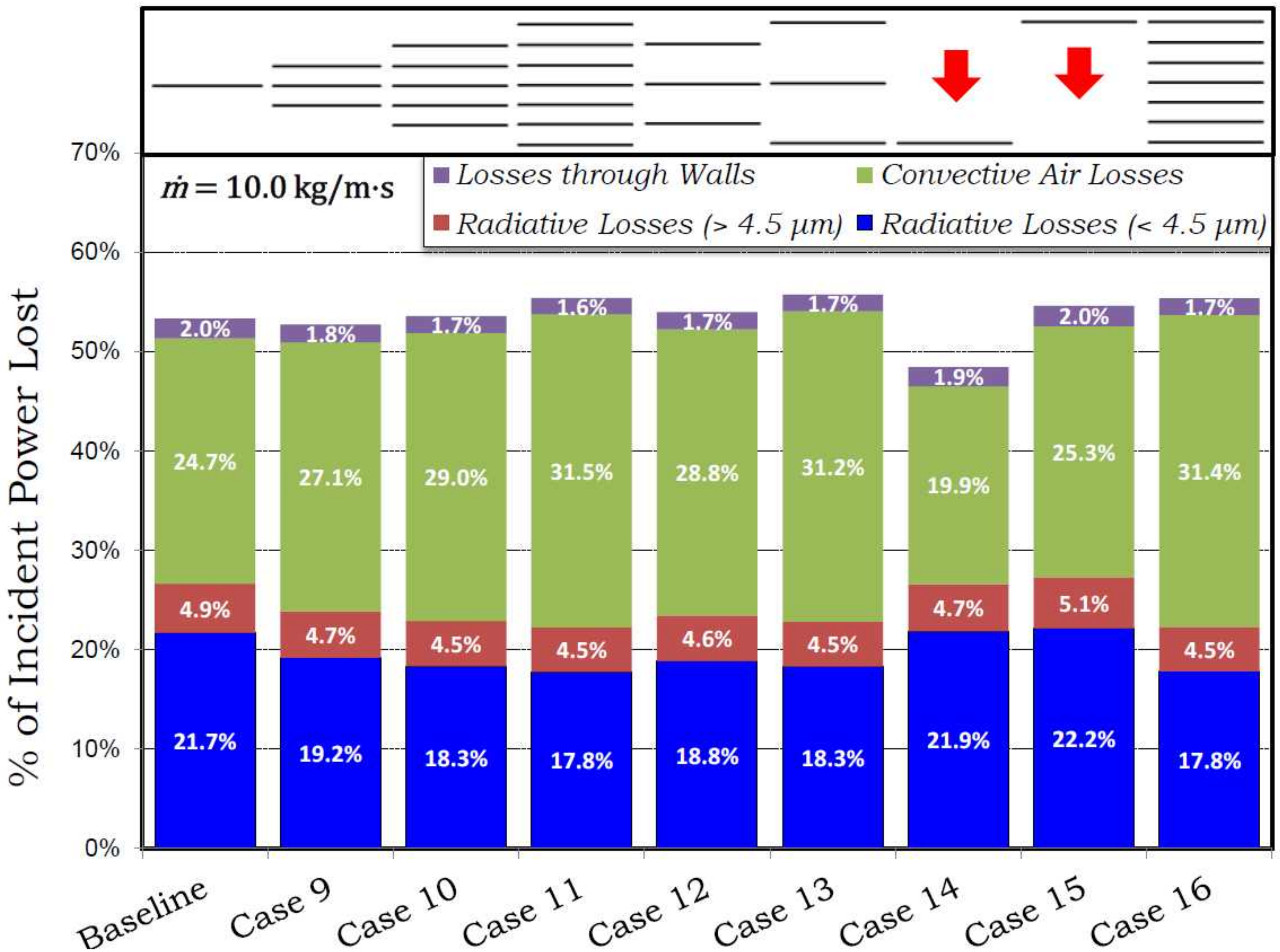

Lower thermal efficiencies in wave-like patterns despite decreased radiative losses

# Parallel Line Efficiency: $T_i$ = 600°C




➡ Lower thermal efficiencies in parallel line patterns despite decreased radiative losses; exception for Case 9

# Parallel Line Losses: $T_i = 600^{\circ}C$

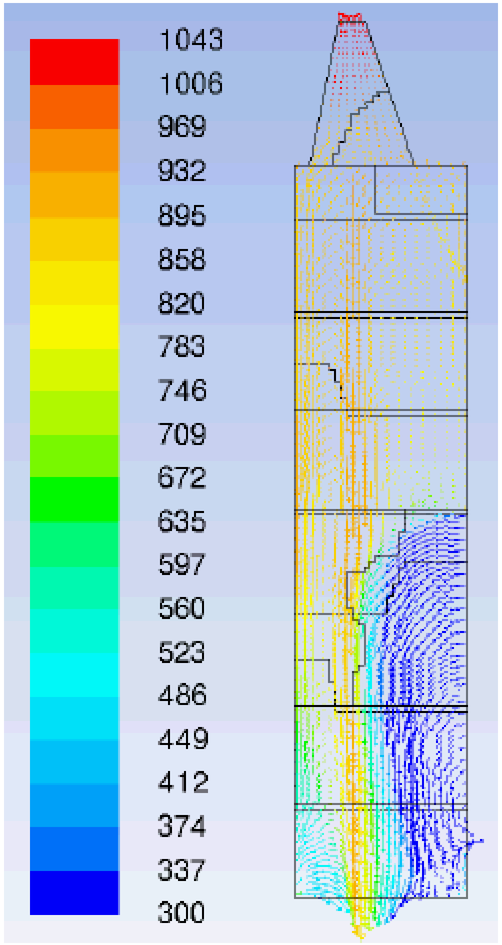



Convective losses were significantly increased. Convective losses changed significantly with release position

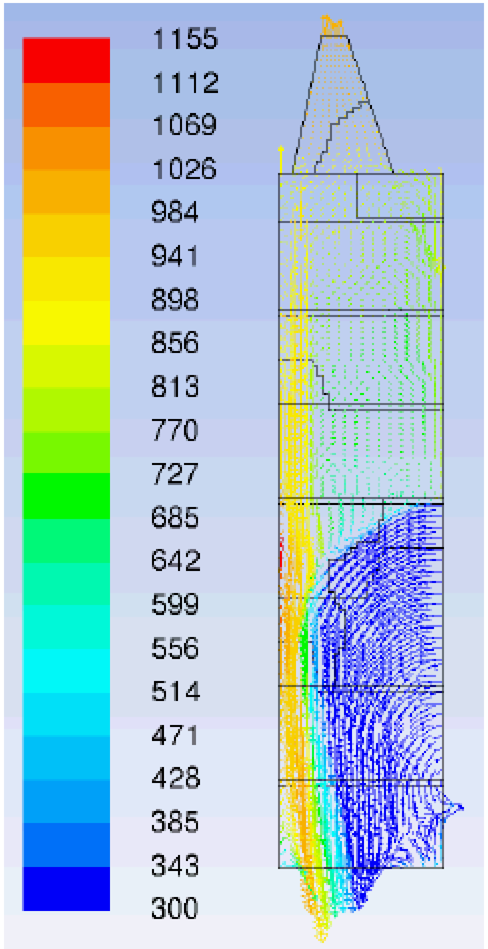
# Flow Field in the Receiver

- In the model, air was allowed to leave through the bottom to the receiver
  - Exaggerated convective losses by entraining cold air through the aperture
  - Not representative of a true receiver

**Velocity vectors colored by temperature (K)**

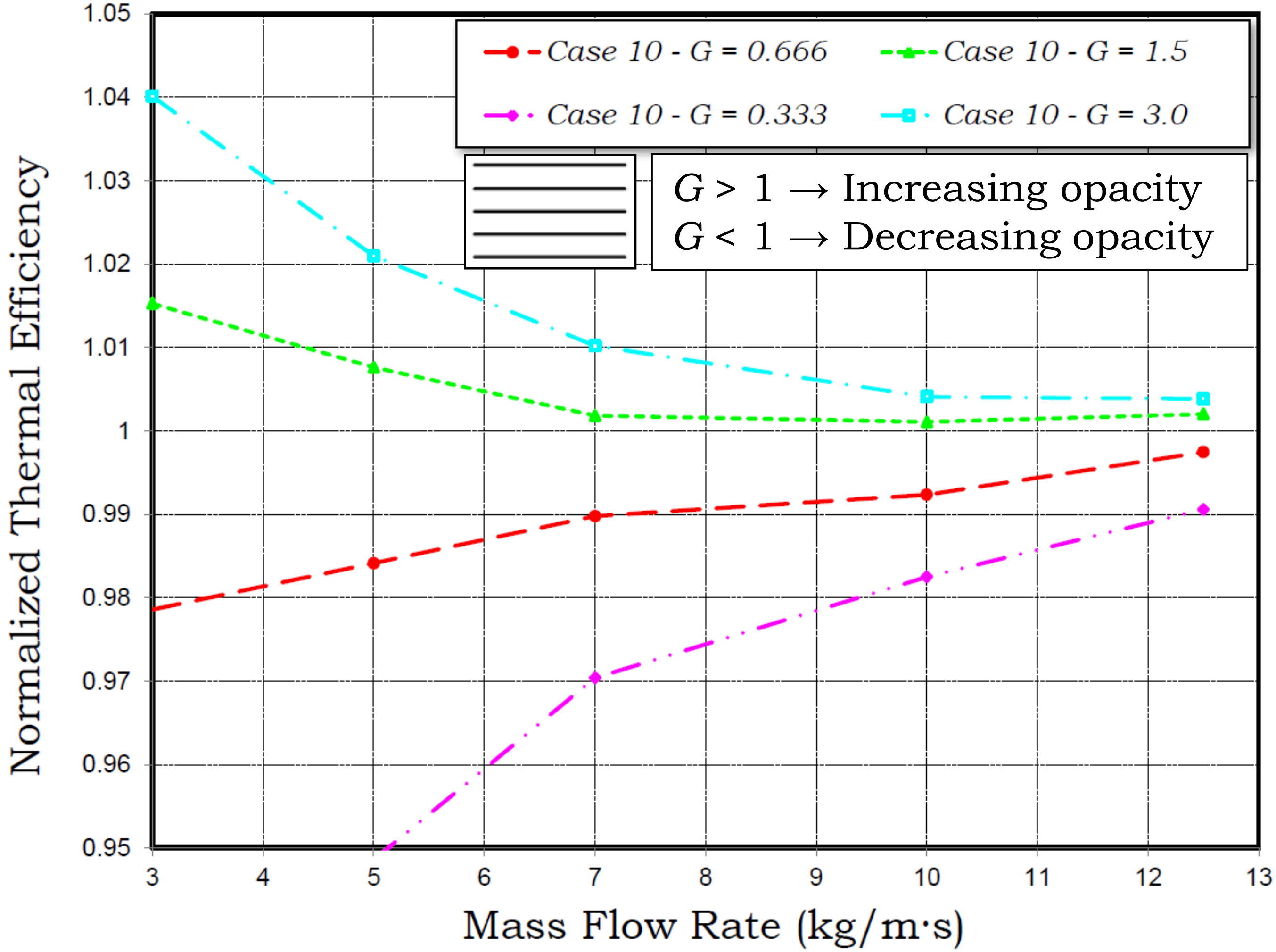



**Baseline**



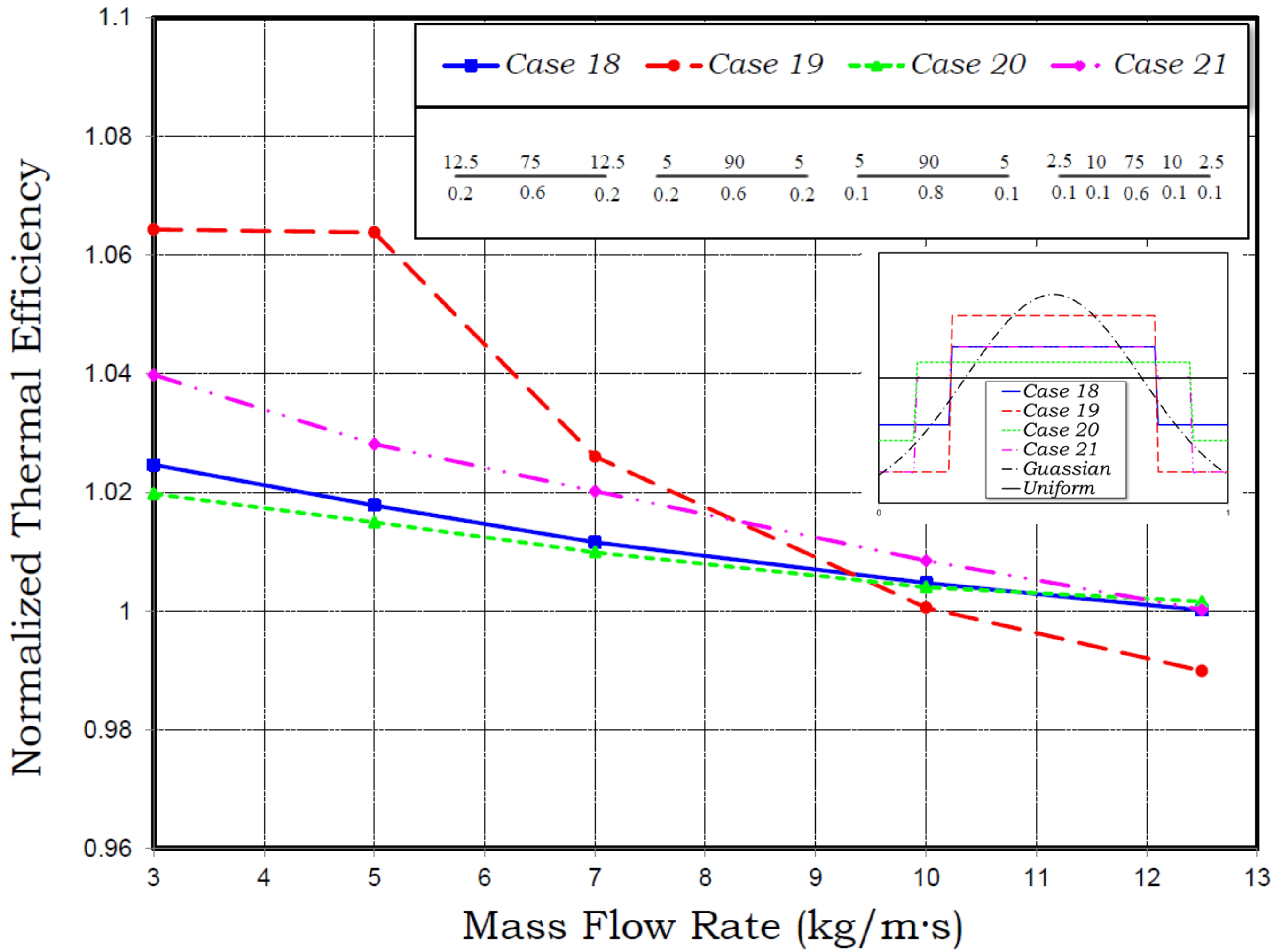

**Case 14**

# Normal Mass Flow Gradients




Increasing the curtain opacity moving away from the aperture increased thermal efficiency; diminishing returns

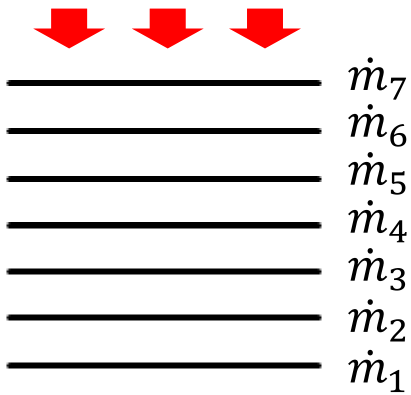
# Lateral Mass Flow Gradients




Higher thermal efficiencies when mass flow rate focused in the center of the curtain; diminishing returns

# Optimization Strategy

- A probabilistic simulated annealing optimization strategy was utilized
  - Investigating parallel line release patterns (all subsets of Case 11)




$$\sum_{n=1}^{7} \dot{m}_n = \dot{m}_{total}$$

$$where \quad 0 \leq \dot{m}_n \leq \dot{m}_{total}$$

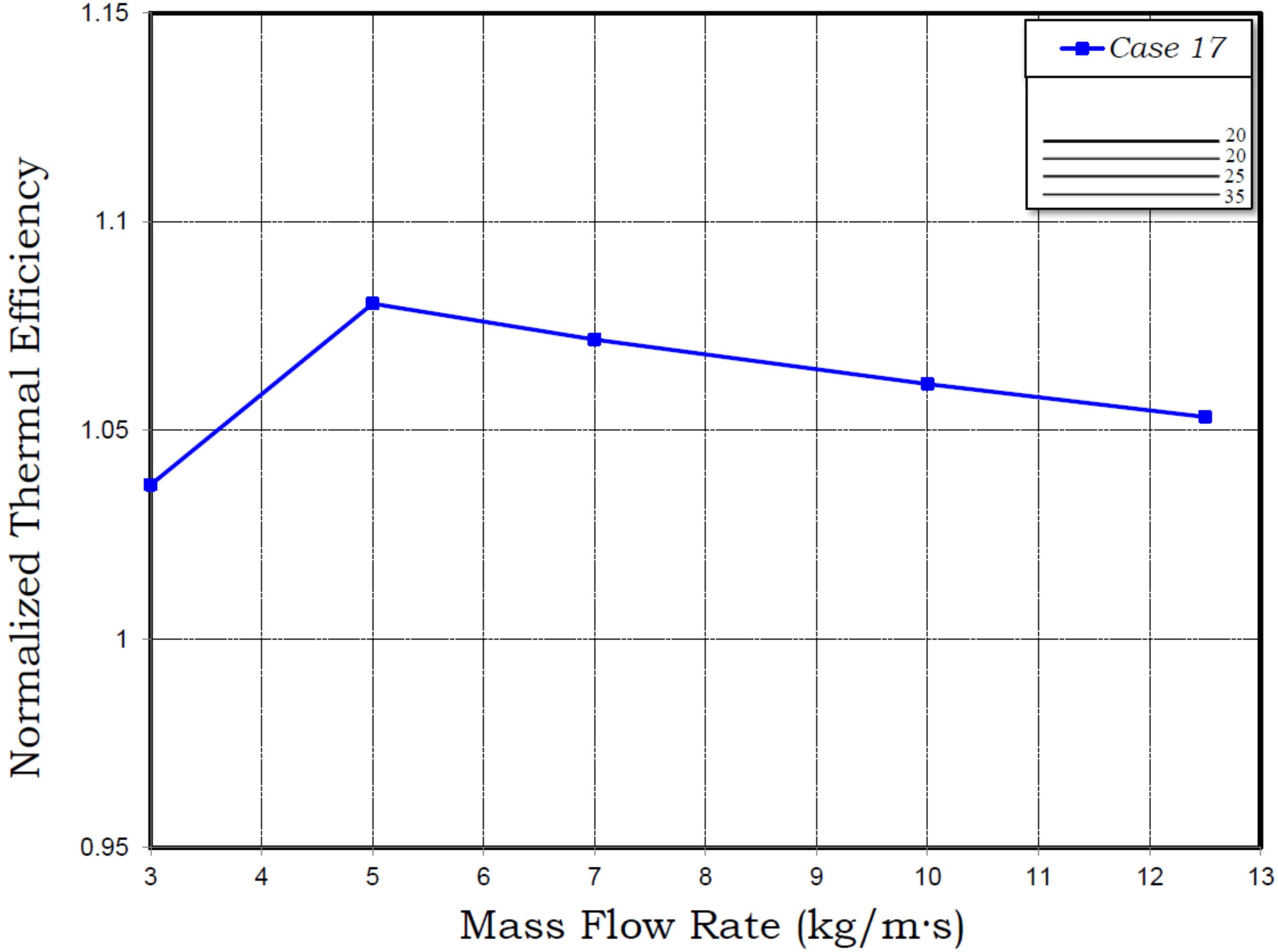
- Looking for insights into other patterns not presently explored

# Optimization Results

- Thermal Efficiency varied from 0.436 ⟶ 0.518
- Case 14 (#1) was found as the most optimal configuration
- Case 17 (#3) was selected as a favorable case to investigate

| # | $\dot{m}_1$ | $\dot{m}_2$ | $\dot{m}_3$ | $\dot{m}_4$ | $\dot{m}_5$ | $\dot{m}_6$ | $\dot{m}_7$ | $\varepsilon_{th}$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 1.000 | - | - | - | - | - | - | 0.518 |
| 2 | - | 0.570 | 0.430 | - | - | - | - | 0.498 |
| 3 | 0.351 | 0.228 | 0.192 | 0.228 | - | - | - | 0.497 |
| 4 | - | 1.000 | - | - | - | - | - | 0.496 |
| 5 | - | 0.505 | 0.495 | - | - | - | - | 0.496 |
| 6 | 0.312 | 0.146 | 0.222 | 0.320 | - | - | - | 0.492 |
| 7 | 0.143 | 0.143 | 0.143 | 0.143 | 0.143 | 0.143 | 0.143 | 0.446 |
| 8 | 0.166 | - | 0.266 | - | - | 0.402 | 0.166 | 0.436 |

# Optimization Results




~4% or higher increase in thermal efficiency over the Baseline case for all mass flow rates

# Preliminary Results

- Investigating Case 3 and 9 demonstrated improved thermal efficiency over the Baseline
  - Recirculation was observed in the receiver trapping hot air behind the curtain

| | $\varepsilon_{th}$ | $\varepsilon_{th} / \varepsilon_{th,Baseline}$ |
|---|---|---|
| Baseline | 0.843 | 1.000 |
| Case 3 | 0.846 | 1.004 |
| Case 9 | 0.865 | 1.025 |