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Evaluating the Thermal Efficiency of Multistage Falling Particle Receivers Subject to Wind

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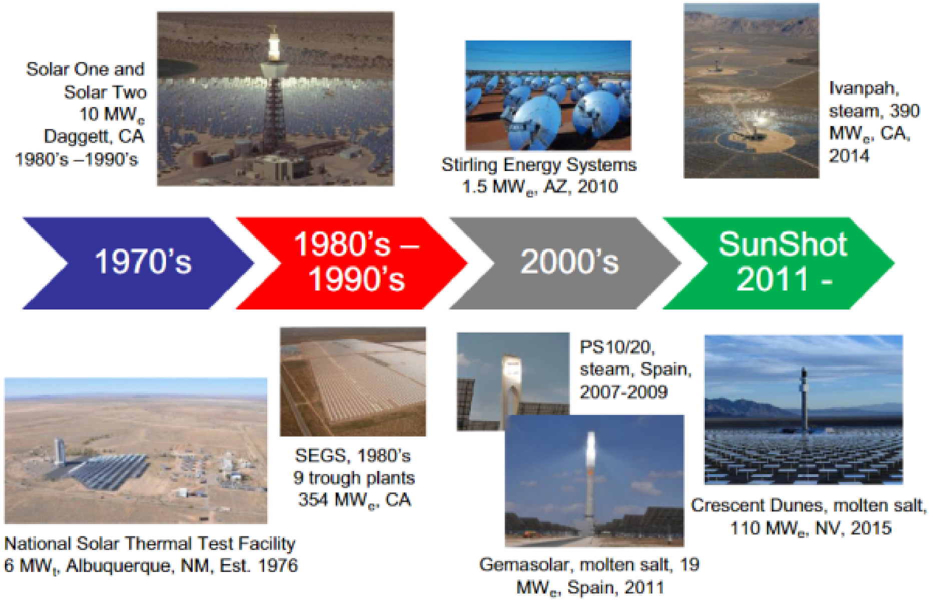
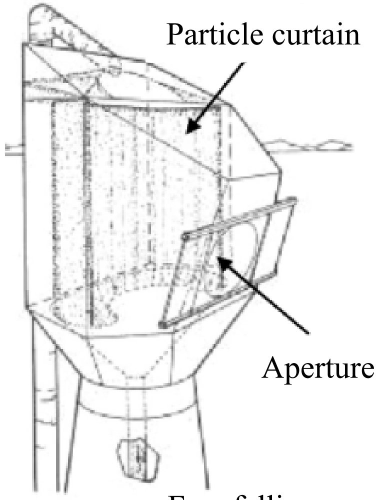
Introduction

Free-falling particle receiver (FFPR) in commercial scale (>100MW_e)

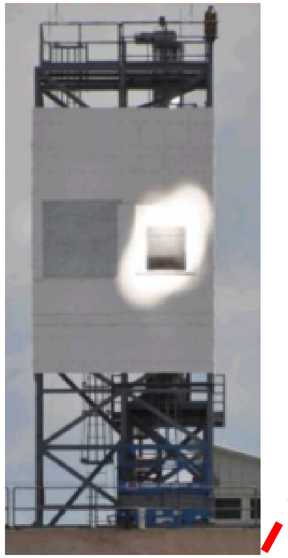
- Central receiver system with ceramic particles (i.e. CARBO HSP, sand, etc).
- Advantages: Direct irradiance, high temperature, on-demand, cost-effective
- Disadvantages: High advective loss, short particle residence time, dispersive particle curtain



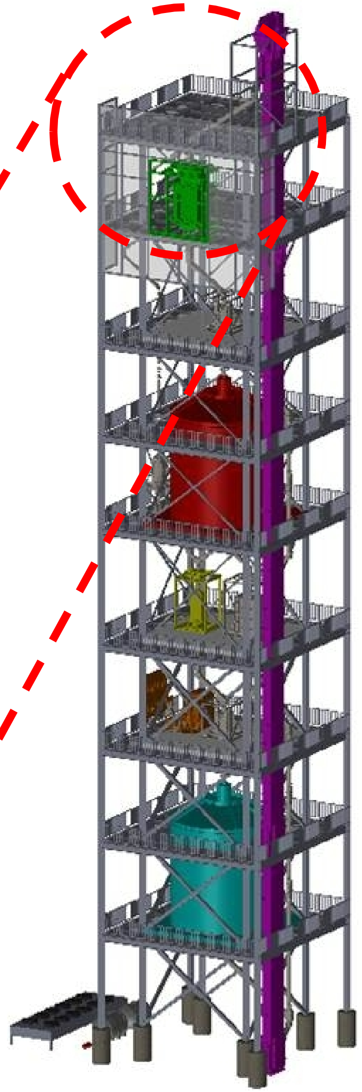
Ho (2017)



Ho (2014)



NSTTF FFPR test loop in 2018



G3P3 concept

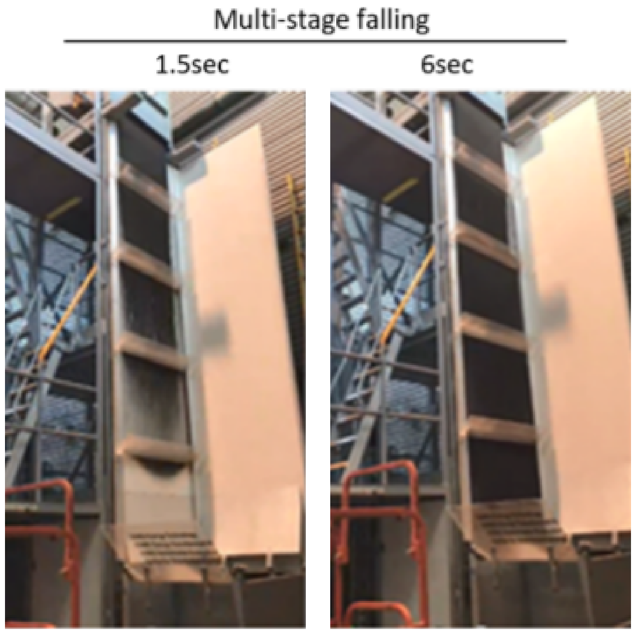
State of the art

Multistage falling particle receiver (MFPR)

- Longer residence time, higher absorptance, better particle stability
- Controlling the advective loss using troughs
- Previous studies: (1) Little investigation of MFPR in commercial scale (>100 MW_e)

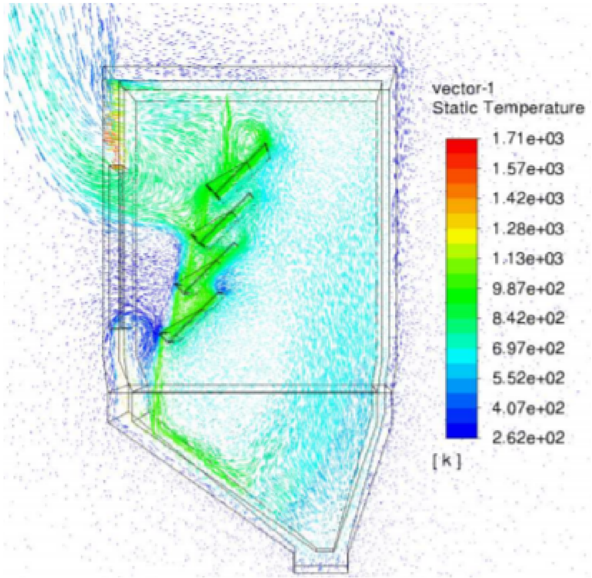
  (2) Little exploration of MFPR design outperforming FFPR in terms of efficiency

  (3) No quantification of MFPR efficiency under various wind conditions



Kim *et al.* (2019)

Yue *et al.* (2020)



Shaeffer *et al.* (2020)

Objectives

1. To optimize MFPR geometry
2. To investigate the wind effects on the MFPR efficiency
3. To gain a robust correlation to predict the thermal performance of MFPR

1. Higher thermal efficiency for commercial capacity CSP
2. Better prediction of MFPR efficiency in realistic conditions
3. Less utilization of experimental/computational resources

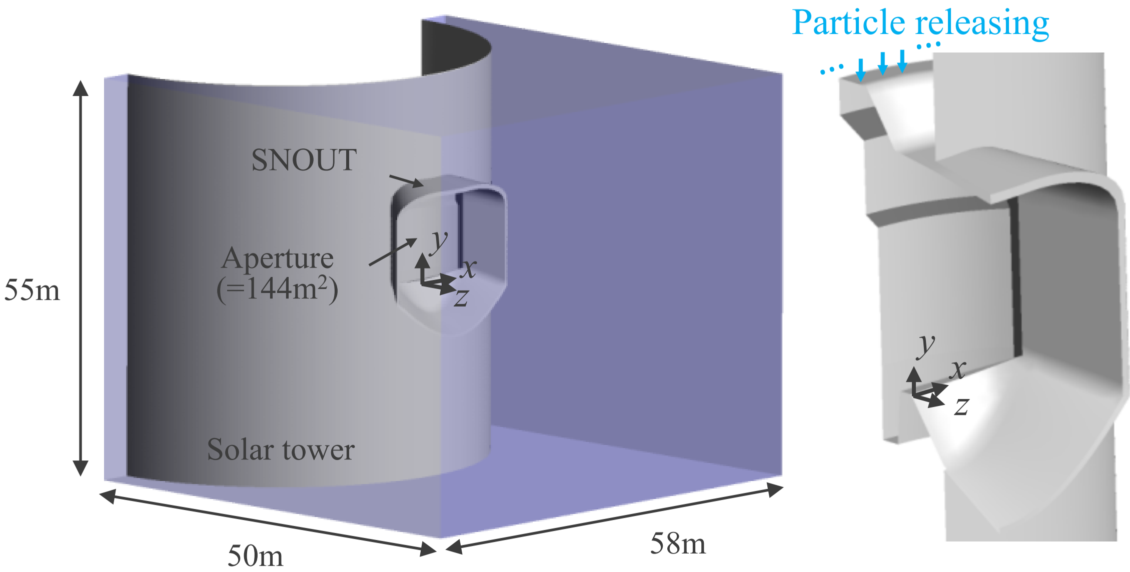
Computational model

Cubit

- Geometry/mesh generation

ANSYS Fluent

- Eulerian-Lagrangian model for the particle-laden flow
- Realizable k-ε turbulence model
- Fluid-thermal coupling
- Non-grey discrete ordinate radiation model for radiative heat transfer
- Forward velocity (~0.3m/s) for trough angle of 30° [Shaeffer *et al.* (2020)]
- Particle drag model: Morsi & Alexander (1972)

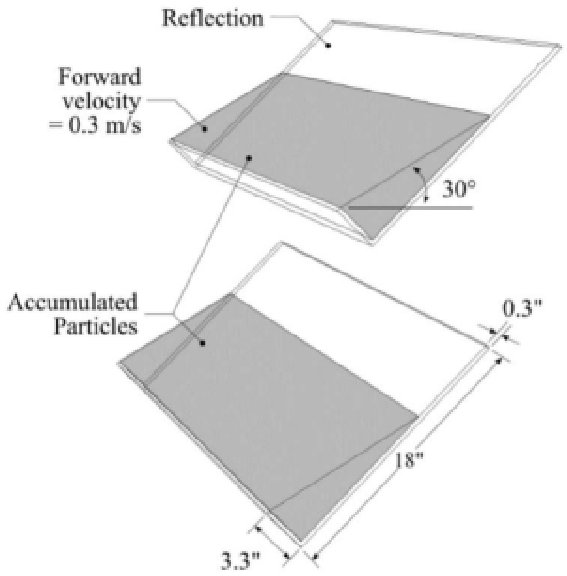


Schematic diagram of computational domain

Parameter range

- Wind directions: N ~ SW
- Wind speeds (U_w): 0 ~ 15m/s
- Incident solar radiation: 100 ~ 200MW
- Inlet temperature: 888.15K
- Particle mass flow rate: 885kg/s

Wind directions

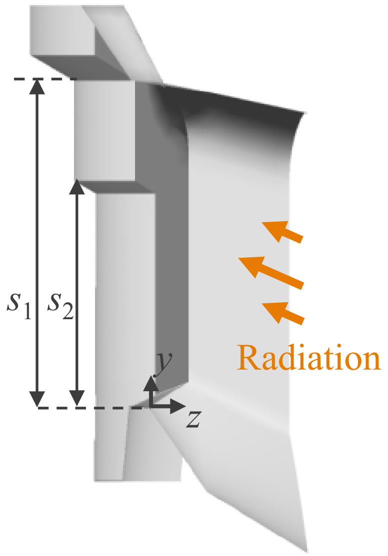


Shaeffer *et al.* (2020)

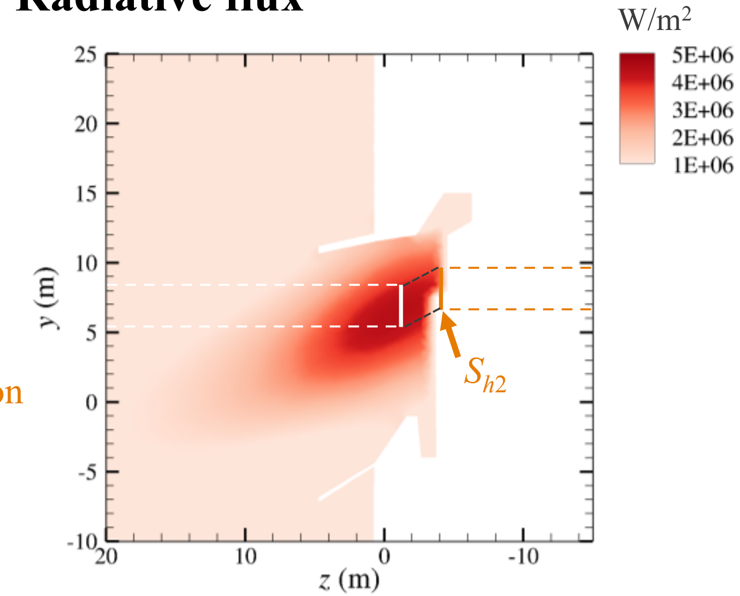
MFPR efficiency in a quiescent condition

- Starting with Sandia's candidate 100MW$_e$ FFPR geometry
- Quiescent conditions
- Incident solar power = 200MW
- Inlet temperature: 888.15K
- Particle mass flow rate: 885kg/s

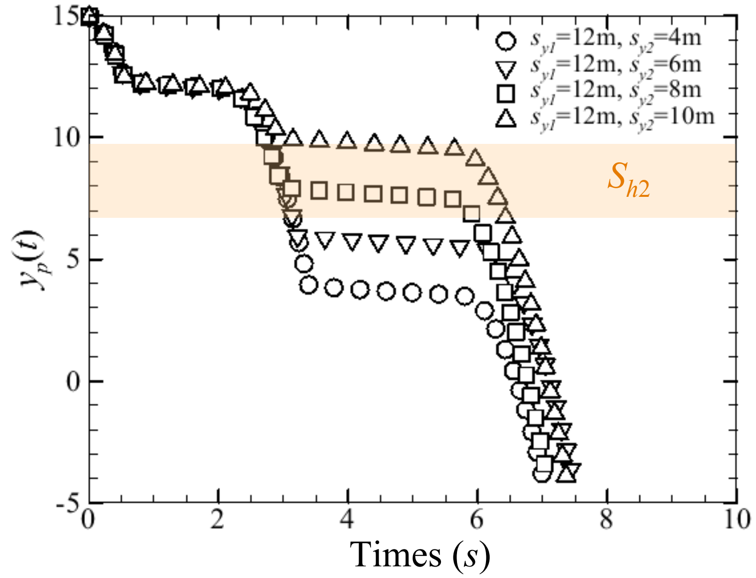
➡ **Intermediate troughs should be placed around S_{h2}**



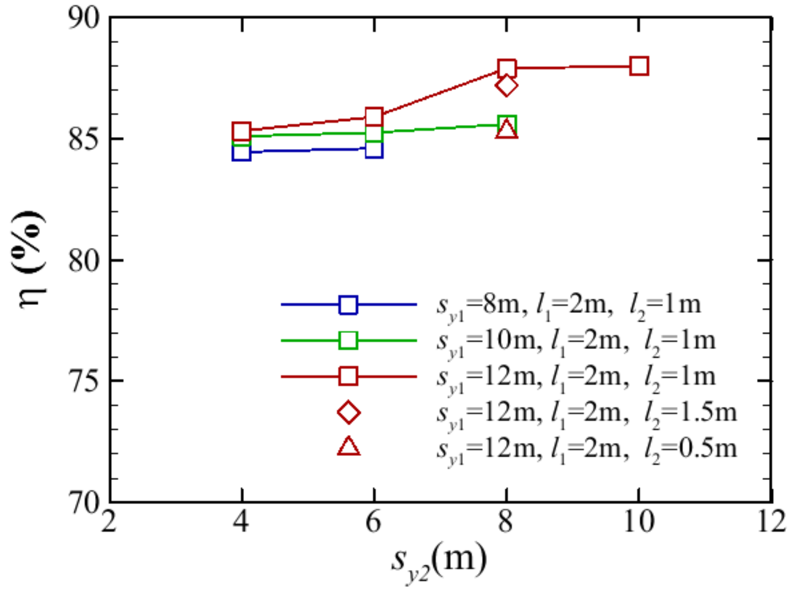
Radiative flux



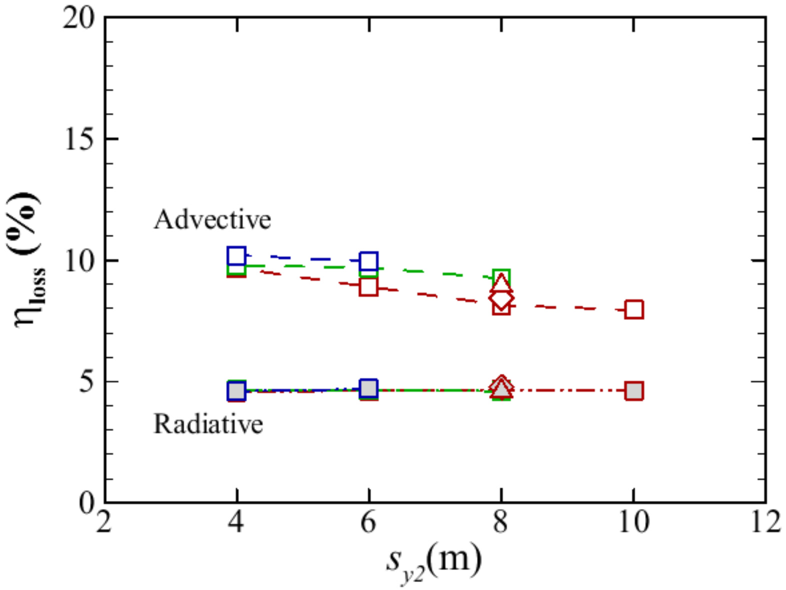
Particle position (y_p)



Efficiency ($\eta = Q_{abs}/Q_{in}$)



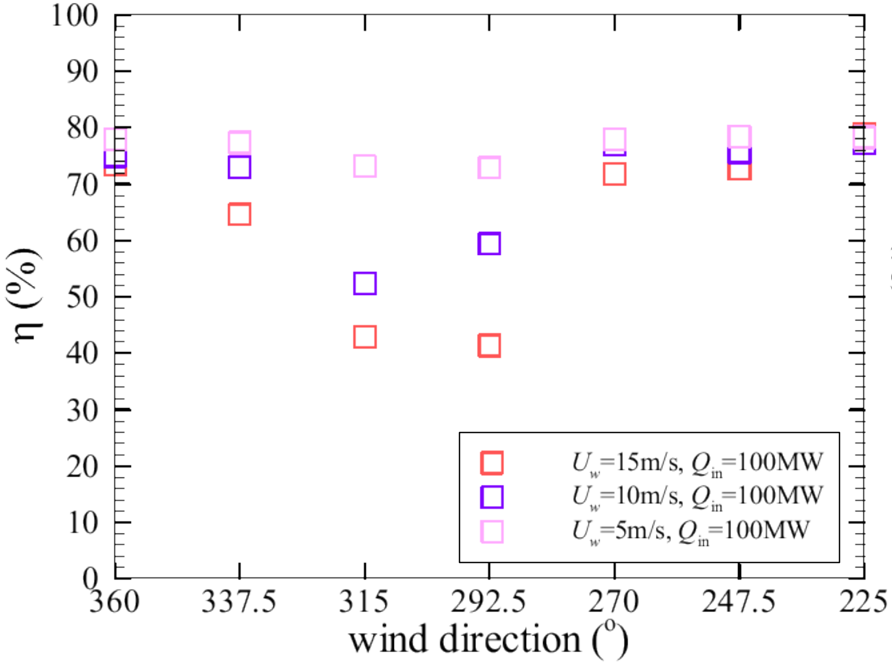
Thermal losses ($\eta_{loss} = Q_{loss}/Q_{in}$)



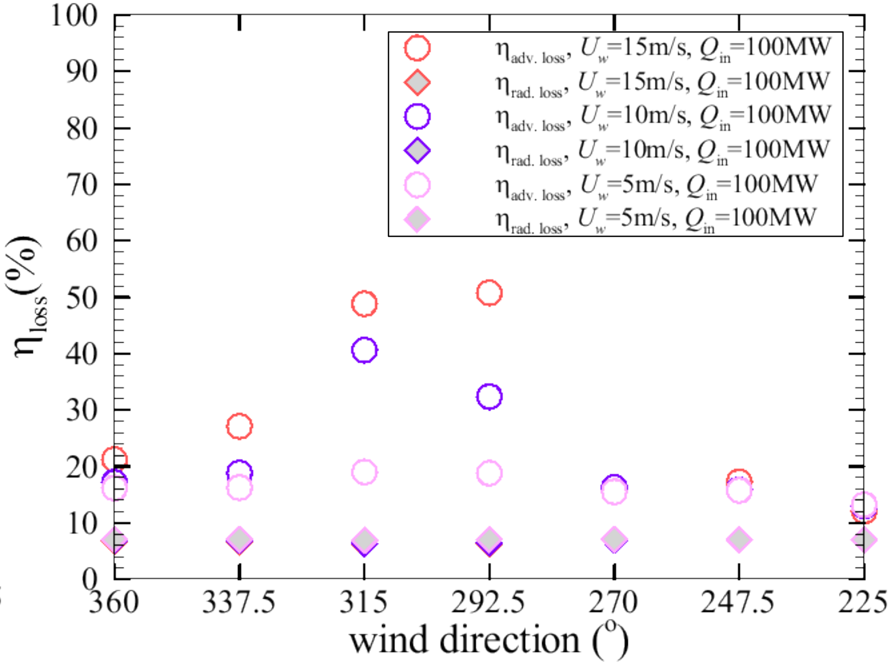
MFPR efficiency subject to wind

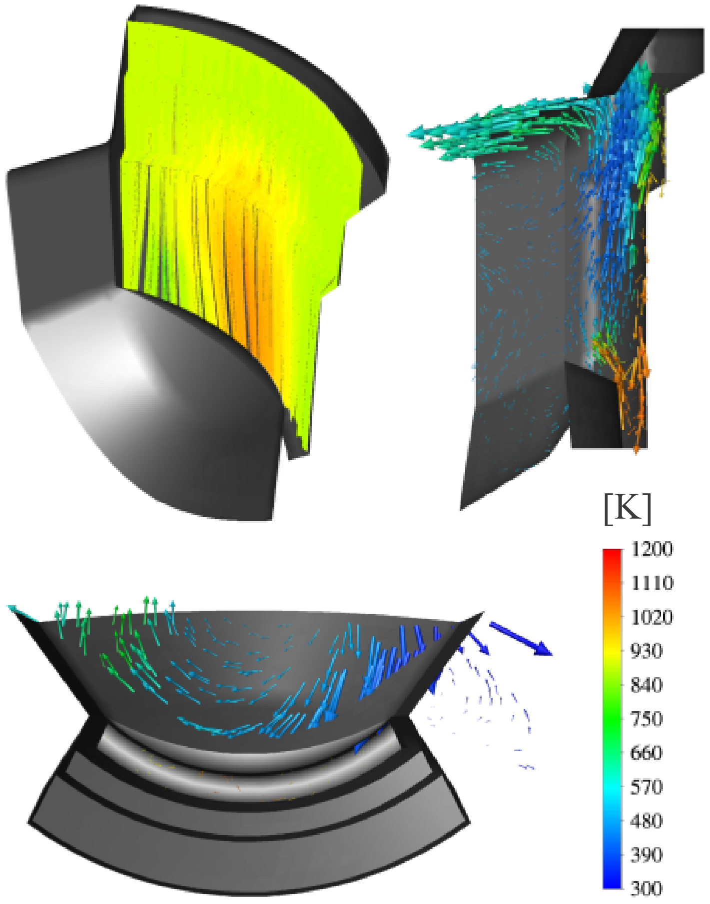
- Advective loss is the main source of efficiency degradation.
- NW or WNW winds are detrimental for thermal efficiency.
- Vortices existing ahead of open aperture intensify the advective loss.
- Effects of wind speed are significant for either NW or WNW winds.

Efficiency ($\eta = \frac{Q_{abs}}{Q_{in}} \times 100\%$)



Thermal losses ($\eta_{loss} = \frac{Q_{loss}}{Q_{in}} \times 100\%$)





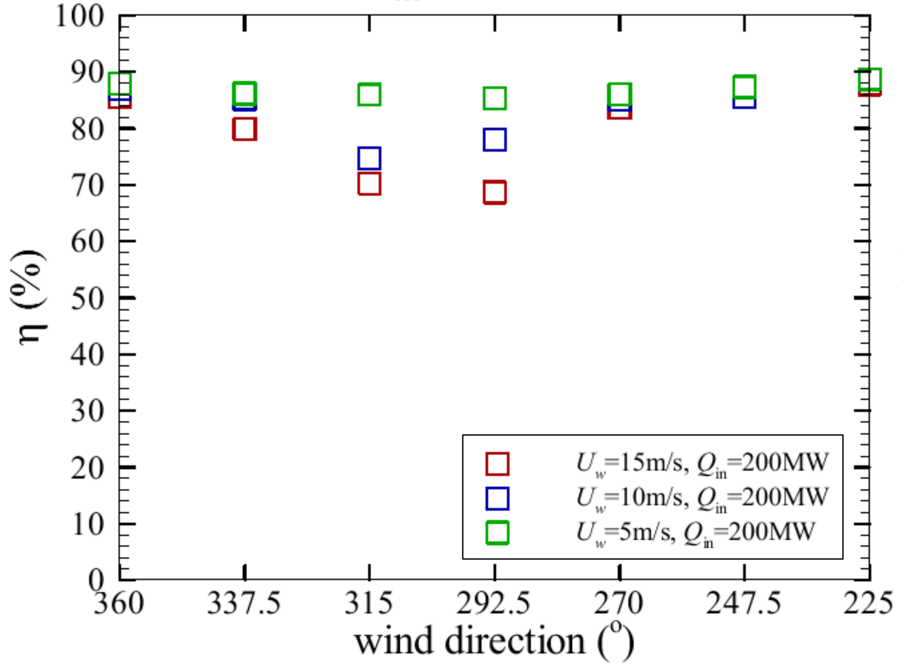
WNW wind (292.5°) , V_w=15m/s, Q_{in}=100MW

MFPR efficiency subject to wind

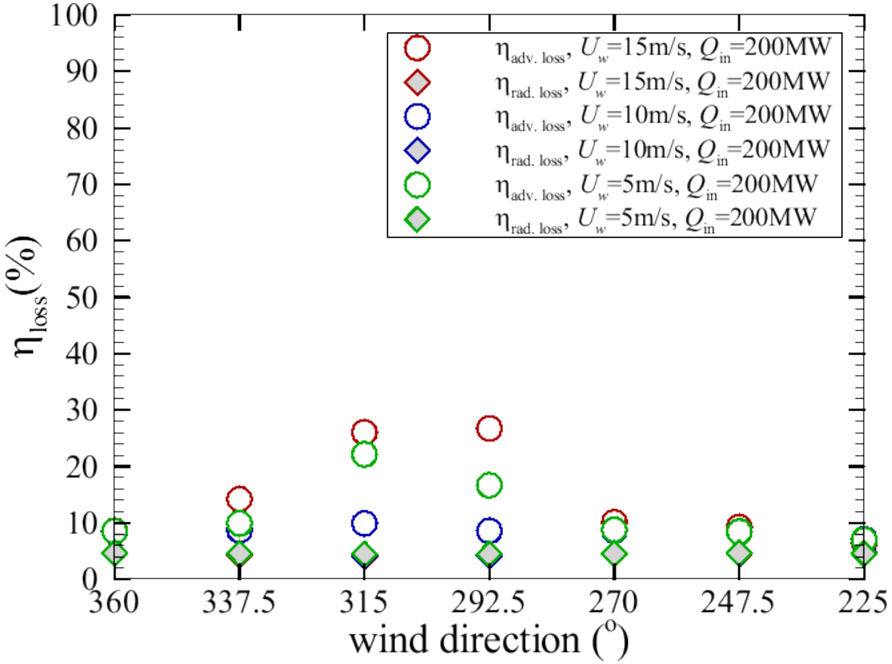
Increasing solar input power ($Q_{in}\uparrow$)

- Marginal change in the magnitude of advective loss (Q_{loss}).
- Lower proportion of the advective loss ($\eta_{loss}\downarrow$).
- Higher proportion of the thermal efficiency ($\eta\uparrow$).

Efficiency ($\eta = \frac{Q_{abs}}{Q_{in}} \times 100\%$)



Thermal losses ($\eta_{loss} = \frac{Q_{loss}}{Q_{in}} \times 100\%$)



Increasing solar input power

$$\downarrow \eta_{loss} = \frac{Q_{loss}}{Q_{in}}$$

Marginal change (Q_{loss})

Increasing (Q_{in})

Correlation development

42 simulations

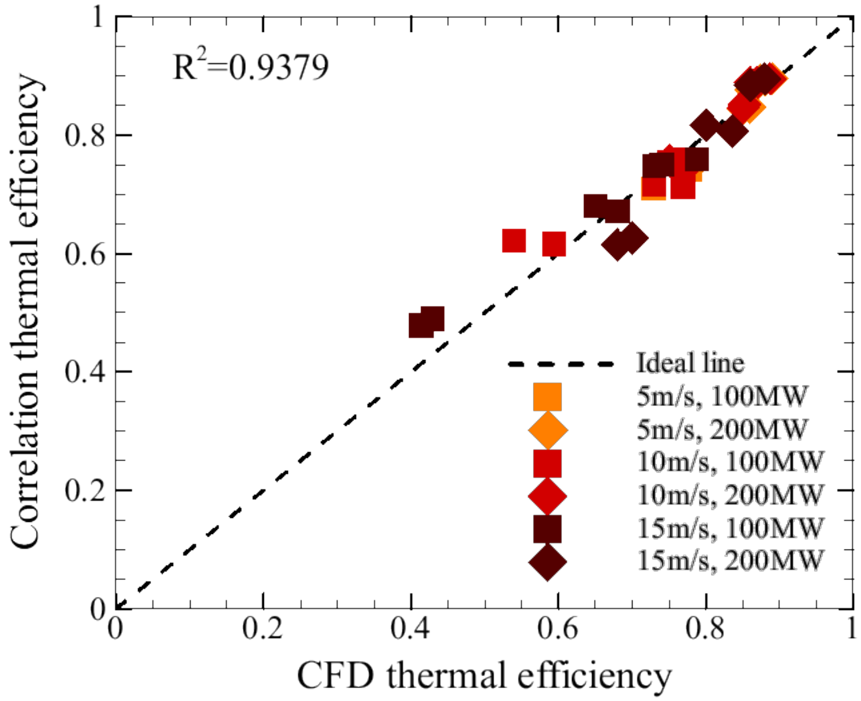
- Incident solar power (Q_{in} = 100 and 200 MW), wind speeds (U_w = 5, 10, and 15m/s), wind directions (θ_w = N, NNW, NW, WNW, W, SW, and S)
- A wind direction modifier is used to provide more accurate fit.
- R-square value ~ 94%, which is sufficient to predict the thermal efficiency.

Correlation function

$$\boldsymbol{A + B(CQ_{in}) + D(CQ_{in})^2 + E(U_wG) + F(U_wG)^2}$$

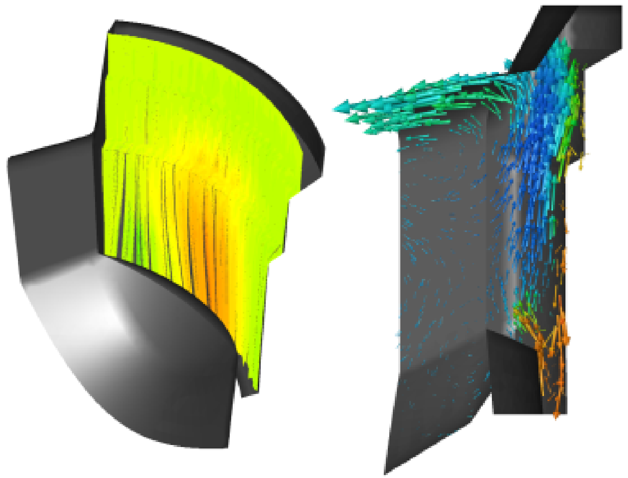
$A = 0.699696$ $D = 0.3760227$
$B = -0.0874869$ $E = -0.0062217$
$C = -0.0030818$ $F = -26.674456$

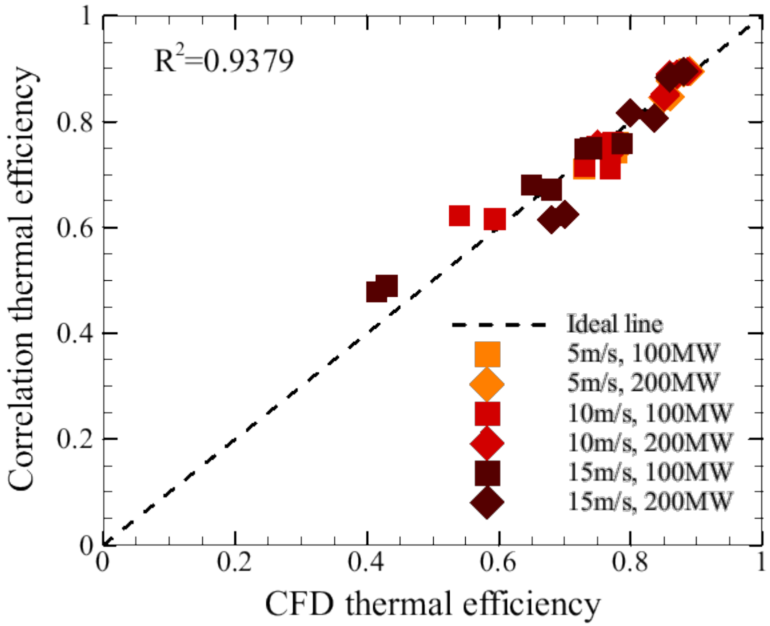
$$G = \exp[-\left(\frac{|\theta_w - 180| - 123}{37}\right)^2$$ (Wind direction modifier)



Summary and conclusions

- **MFPR geometry in a quiescent condition**
  - The optimized MFPR geometry provides the thermal efficiency of 88%.
- **MFPR efficiency under various wind conditions**
  - Wind direction is the dominant factor to degrade the thermal efficiency.
  - NW/WNW winds form a vortical structures near the open aperture as detrimentally degrading thermal efficiency.
  - Increasing wind speed has adverse effects on the efficiency for NW or WNW winds.
  - Lower solar input power increases the proportion of advective loss.
- **Correlation development**
  - R-square value ~ 94%, which is sufficient to predict the thermal efficiency.
  - Different parameter inputs also need to be investigated for robustness. (i.e. Particle inlet temperature, particle mass flow rate, etc.)





Thank you