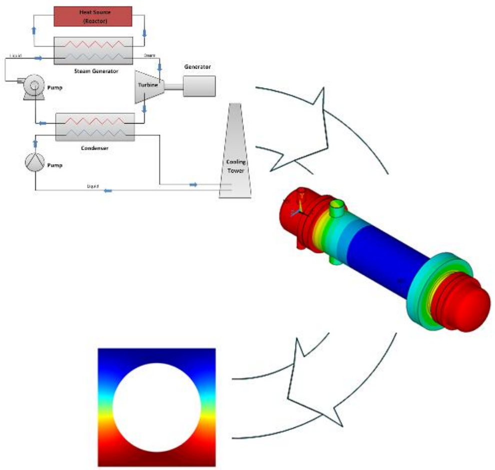
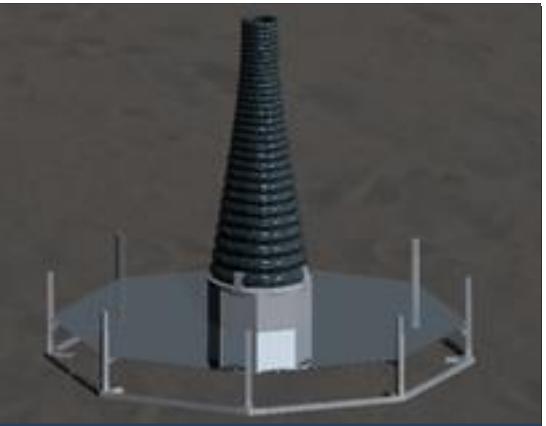




Applied Mathematical Evaluation of Solar Tower Systems: Hybrid Renewable Energy Development

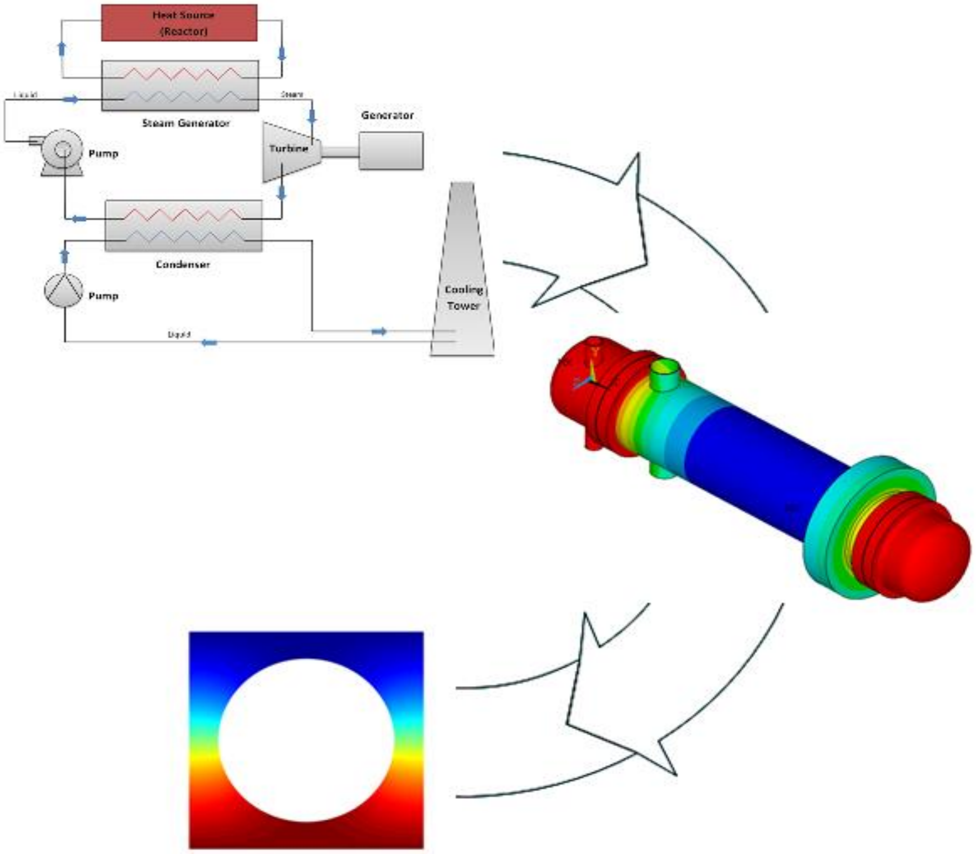
Nima Fathi
Mechanical Engineering Department
University of New Mexico

PIMS Workshop on Mathematical Sciences and Clean Energy Applications

ESB 1012, UBC
May 23, 2019

Outline

- Motivation and Background
- Analytical Study
- Double-Inlet Collector
- Inflatable Tower
- Combined Solar Cycle
- Related Investigations



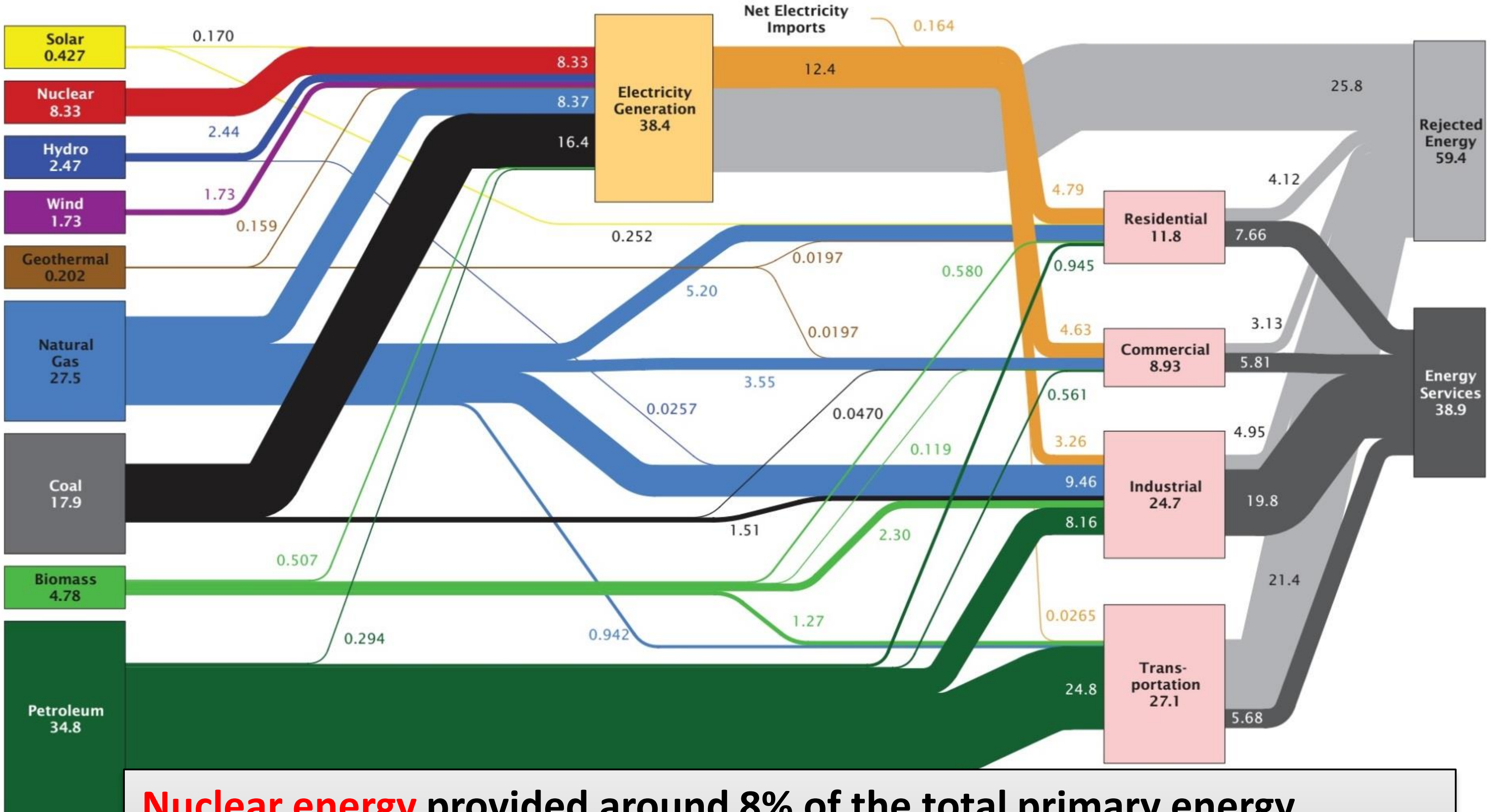
Motivation

- Fossil fuels are still the dominant source of energy.

- The share of solar energy is still very low (0.43% of the US energy consumption in 2015 and 0.58% in 2016)

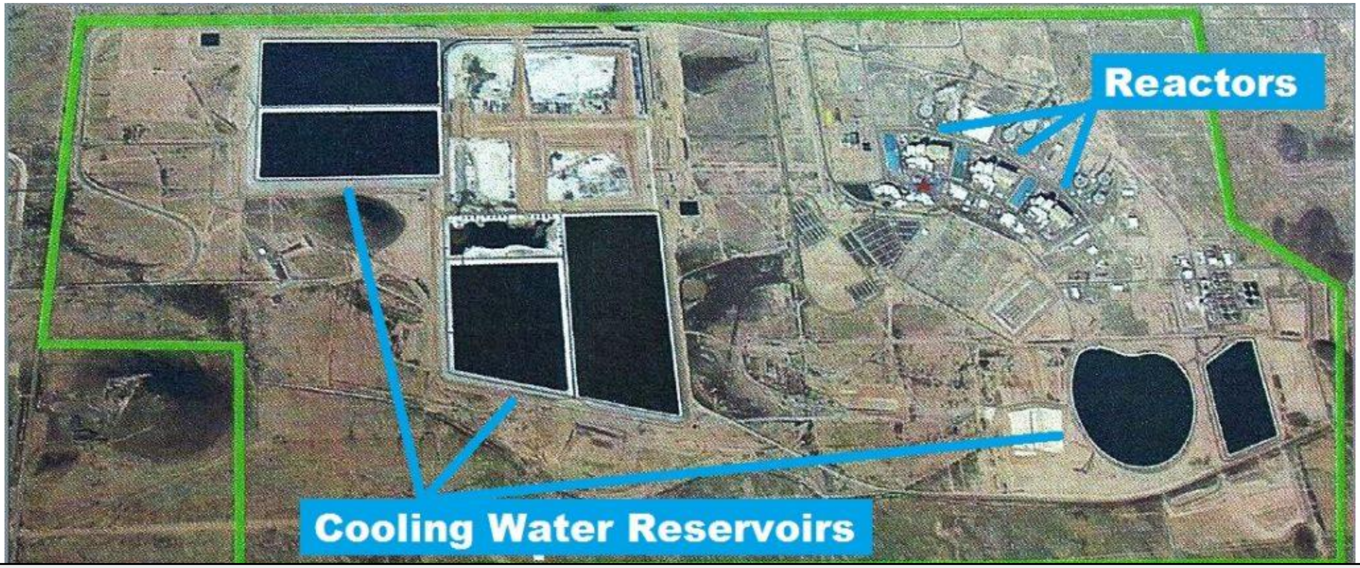
Motivation/Bad News!

units in quadrillion Btu



Nuclear energy provided around 8% of the total primary energy consumption and all of it was used for electricity generation.
The share of solar energy in 2015 US electricity generation was just 0.4% in 2015 and 0.6% in 2016.

Another Motivation/Bad News!



- The single **largest** consumers of fresh water in the United States are **thermal power plants** used to produce electricity.
- Approximately **half** of all fresh water consumed in the United Sates is used to absorb waste heat from thermal power plants.
- Typically, this water is either returned to the body of water from which it was extracted, or more commonly it is evaporated to the atmosphere in a cooling tower.
- Some nuclear power plants (Palo Verde in particular) are currently restricted from expansion by the lack of fresh water.

Similar Historical Approach

Burning wood or gas

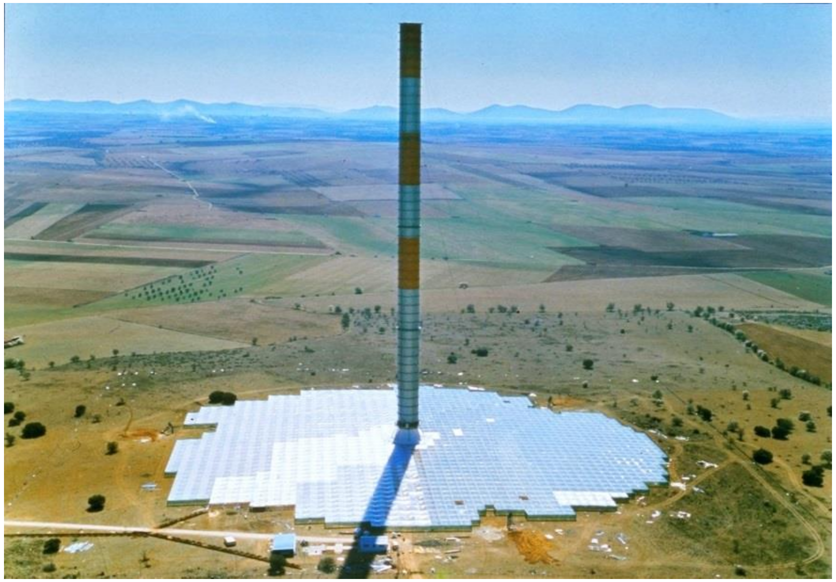
No Change In Energy Policy for 300,000 Years,

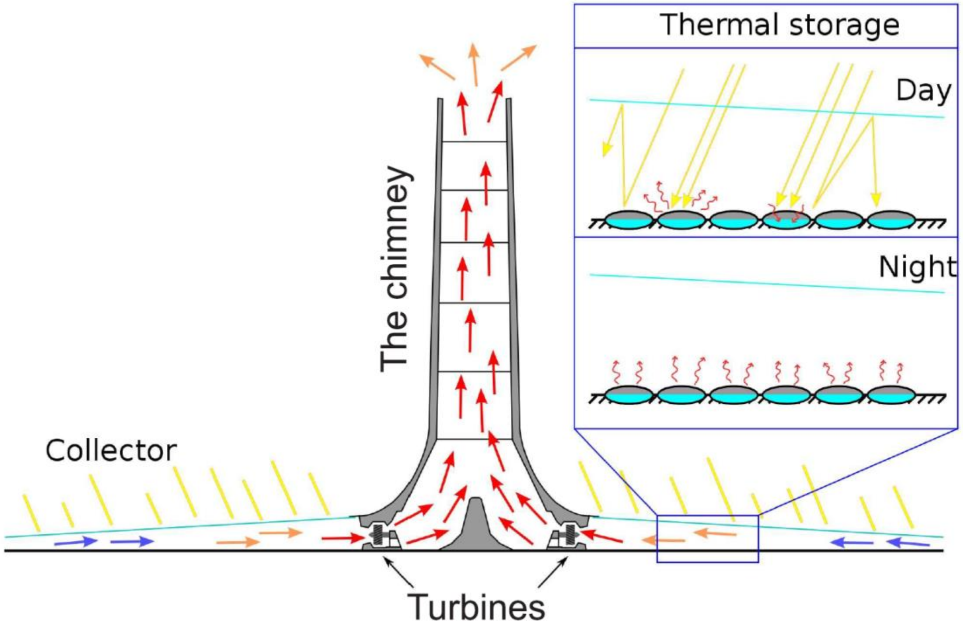
Throw a Little Carbon on the Fire

Solar Power Towers

- Concentrated Solar Power Plants
- Solar Chimney Power Plants

Solar Chimney Power Plant





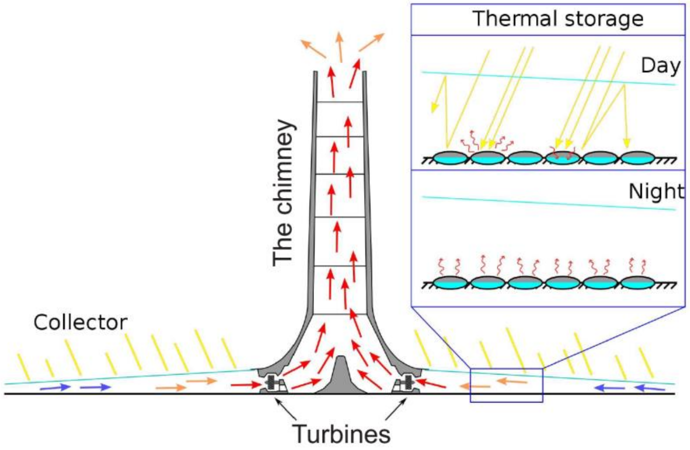
Our Goal

- Having solar towers more efficient to be utilized in hybrid energy systems

- To address the water consumption issue in the cooling process

Manzanares Prototype

Prototype component	Size (m)
Mean collector radius	122.00
Collector height	1.85
Chimney radius	5.08
Chimney height	196
Rotor blade length	5



- Isidoro Cabanyes, Spanish colonel proposed this idea(1903).
- The most famous prototype built in Manzanares at Spain in 1982 and rebuilt in 1989.
- China recently started to invest on this industry.

Analytical Study

$$\frac{dA}{A} + \frac{d\rho}{\rho} + \frac{du}{u} = 0 \quad \text{(Continuity)}$$

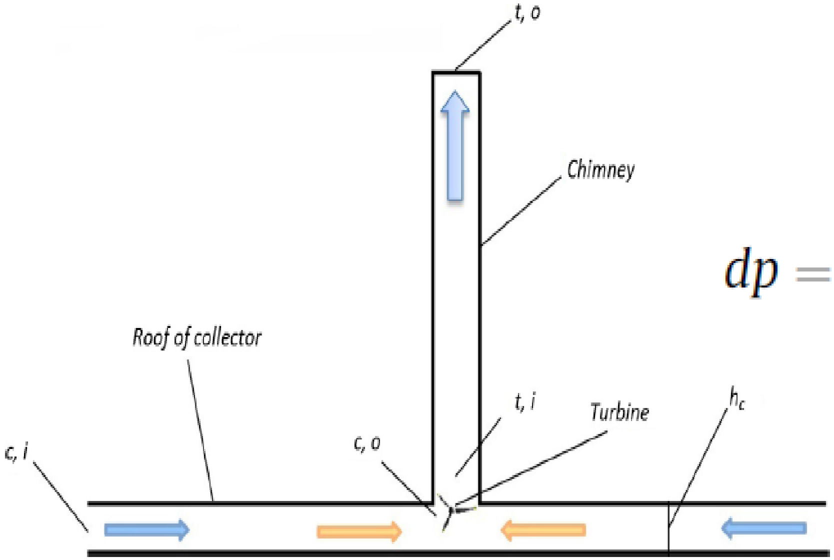
$$dp + \rho u du = 0 \quad \text{(Momentum)}$$

$$c_p dT - dq + u du = 0 \quad \text{(Energy)}$$

$$dp = d(\rho RT) \quad \text{(State)}$$

$$\dot{W} \simeq \frac{\dot{m}(p_{c,o} - p_{t,i})}{\rho_{turb}}$$

Analytical Study-Collector



$$dp = \frac{\dot{m}^2}{\rho}\left(\frac{dA}{A^3} - \frac{q''(2\pi r)dr}{\dot{m}(2\pi r h_c)^2 T c_p} + \frac{udu}{A^2 c_p T} + \frac{dp}{A^2 p}\right)$$

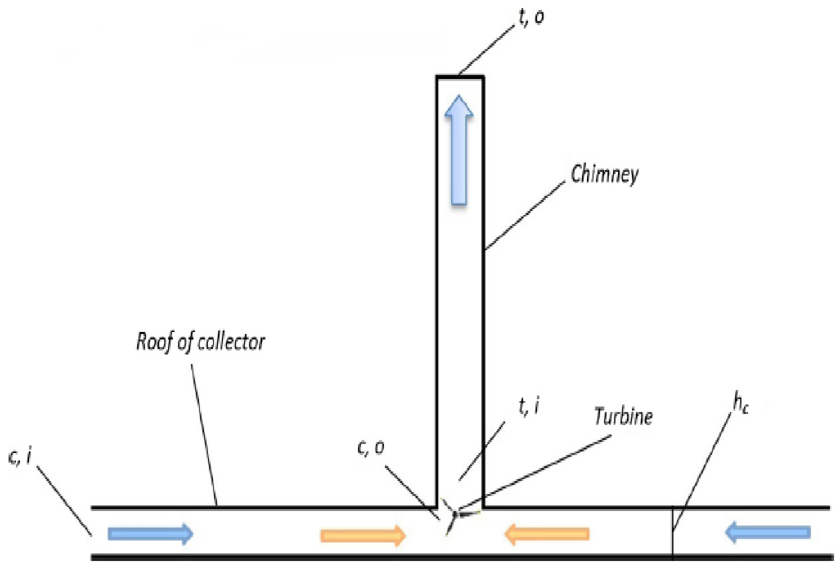
$$p_{c,o} - p_{c,i} \simeq \left[\frac{\dot{m}^2}{2\rho_{m,c}}\left(\frac{1}{A_{c,i}^2} - \frac{1}{A_{c,o}^2}\right) + \frac{q''\dot{m}}{2\pi h_c^2 c_p \rho_{m,c} T_{m,c}} ln\frac{r_{c,i}}{r_{c,o}}\right]$$

Analytical Study-Tower

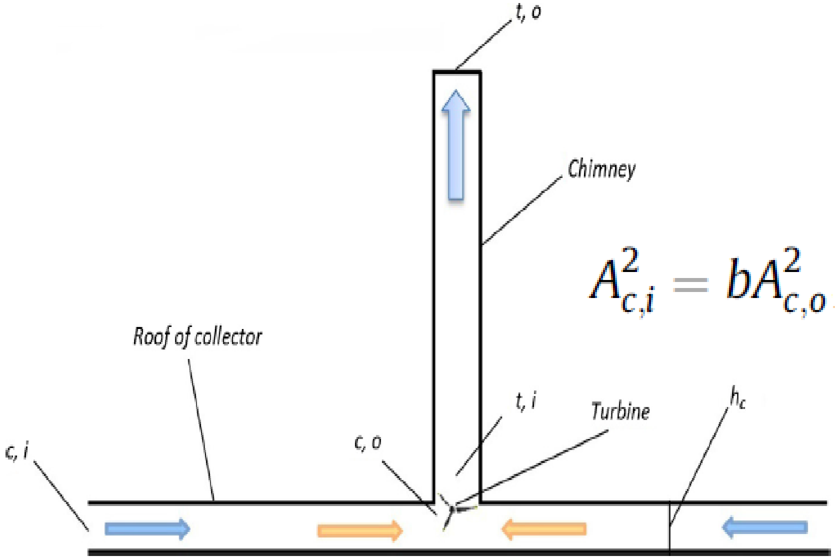
$$p_{t,o} = p_{\infty}\left(1 - \frac{gh_t}{c_p T_{\infty}}\right)^{\left(\frac{c_p}{R}\right)}$$

$$\rho_{t,i} = \rho_{c,o} = \rho_{\infty}\left(1 + \frac{T_{\infty} - T_{c,o}}{T_{\infty}}\right)$$

$$p_{t,o} - p_{t,i} \simeq -\rho_{m,t} g h_t - \frac{\dot{m}^2}{2\rho_{m,t}}\left(\frac{1}{A_{t,o}^2} - \frac{1}{A_{t,i}^2}\right)$$



Analytical Study-Power Calc

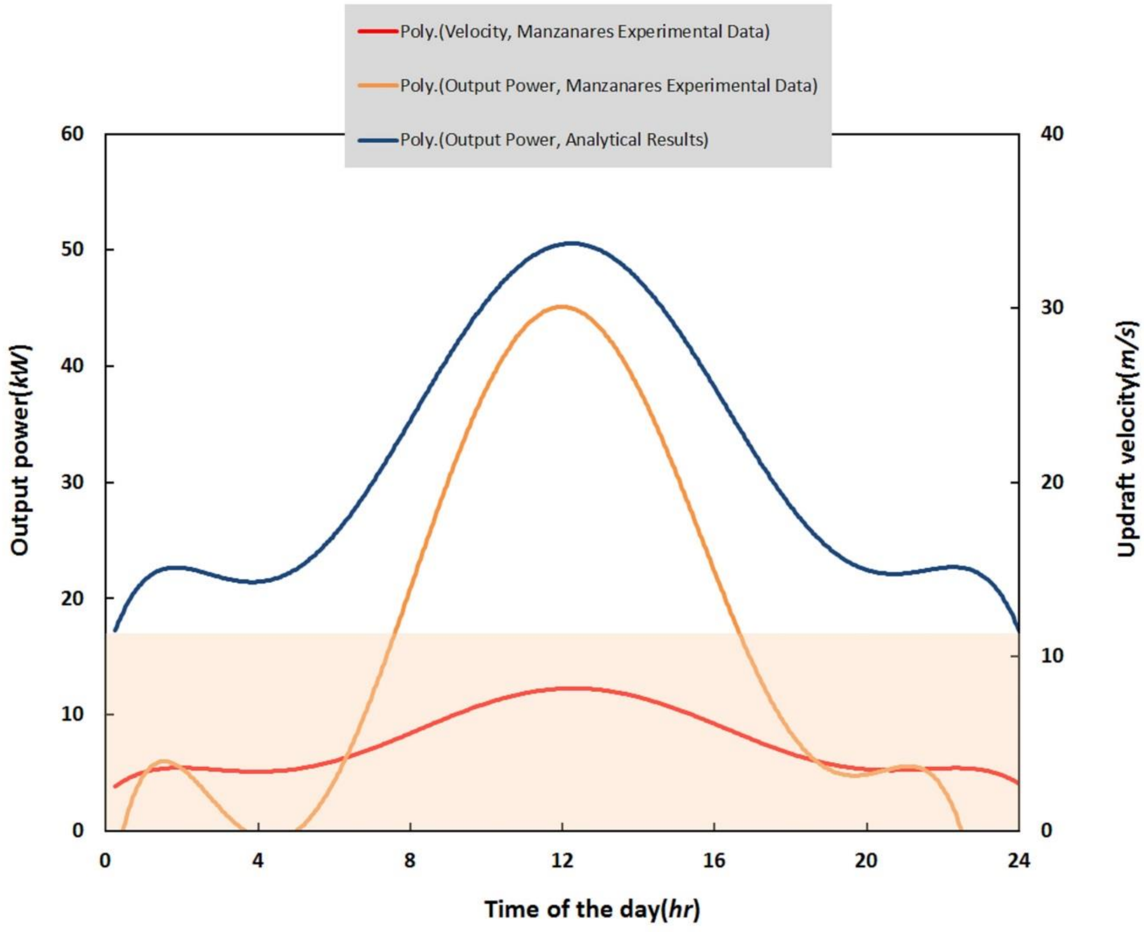


$$A_{c,i}^2 = bA_{c,o}^2$$

$$\dot{W} \simeq \frac{\dot{m}(p_{c,o} - p_{t,i})}{\rho_{turb}}$$

$$\dot{W} \simeq \frac{\dot{m}}{(\rho_{c,o} + \rho_{t,i})/2}\left[\frac{-\dot{m}^2}{2\rho_{m,c}}\left(\frac{b-1}{bA_{c,o}^2}\right) + \frac{q''\dot{m}}{2\pi h_c^2 c_p \rho_{m,c} T_{m,c}} ln\frac{r_{c,i}}{r_{c,o}} + (\rho_\infty - \rho_{m,t})gh_t\right]$$

Analytical Study-Power Calc.

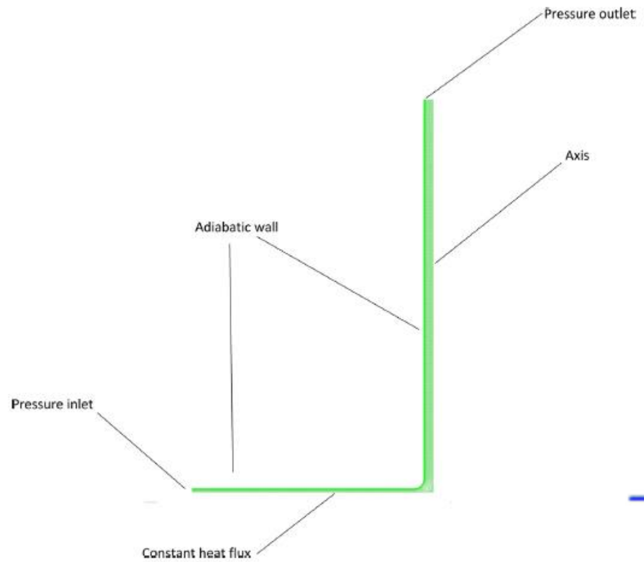


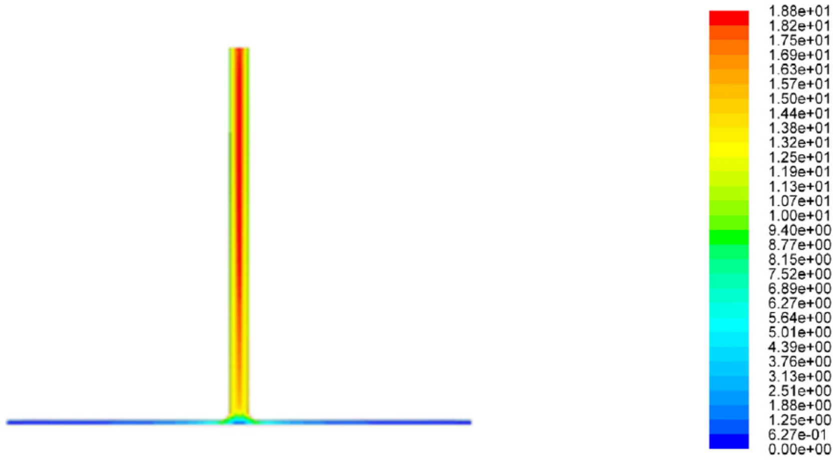
Computational Study

Turbulent Flow

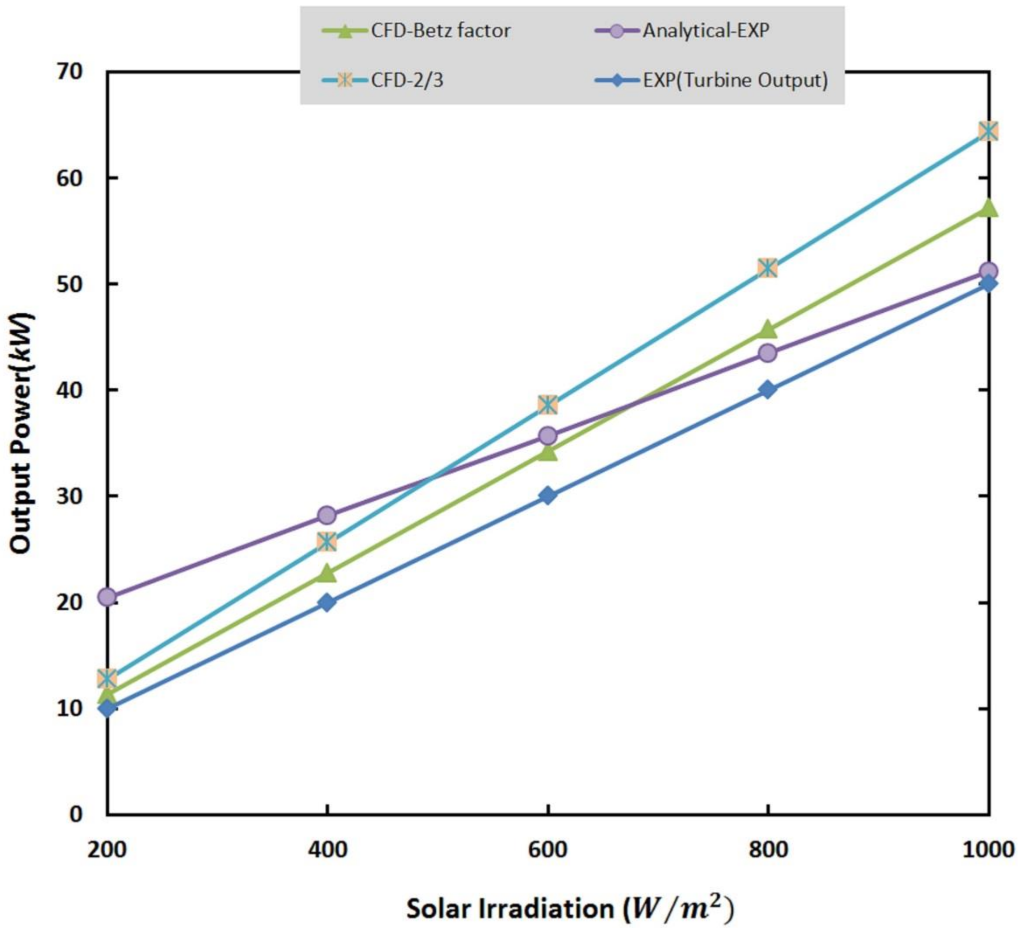
Air

Natural Convection

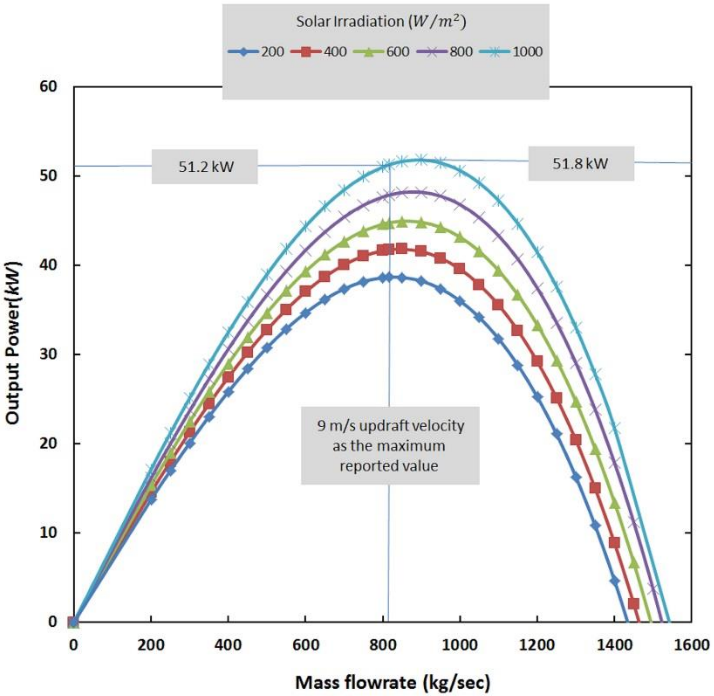


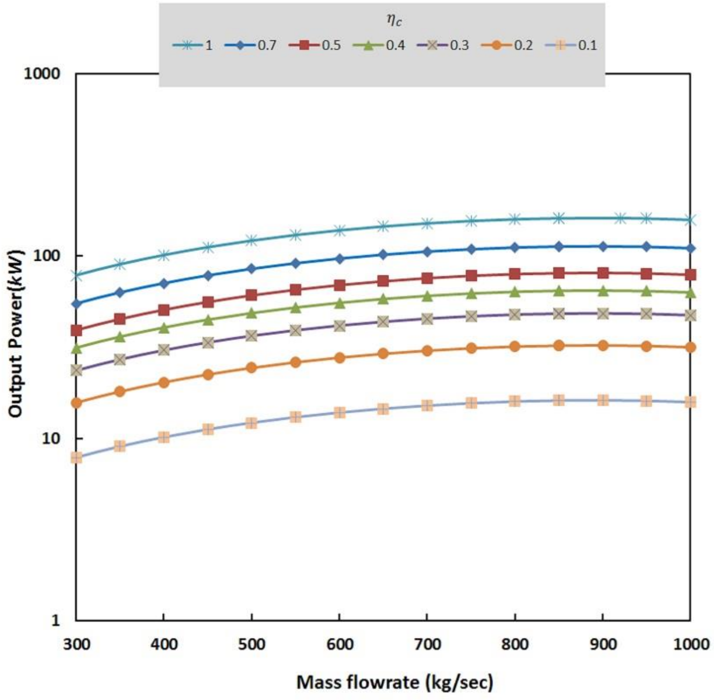


Comparative Study - Evaluation

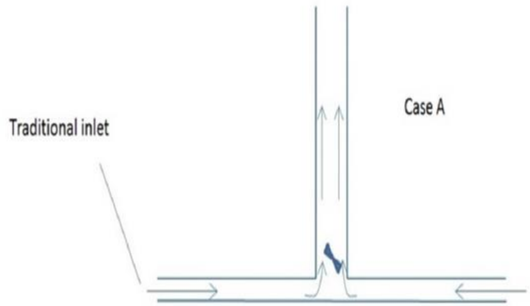


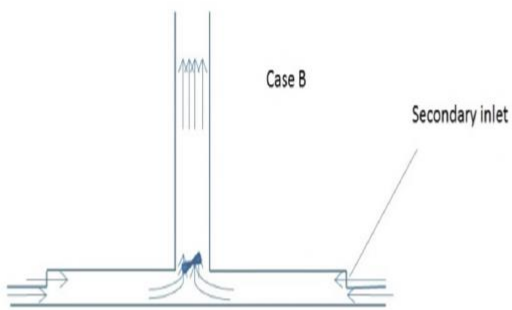
Analytical Power

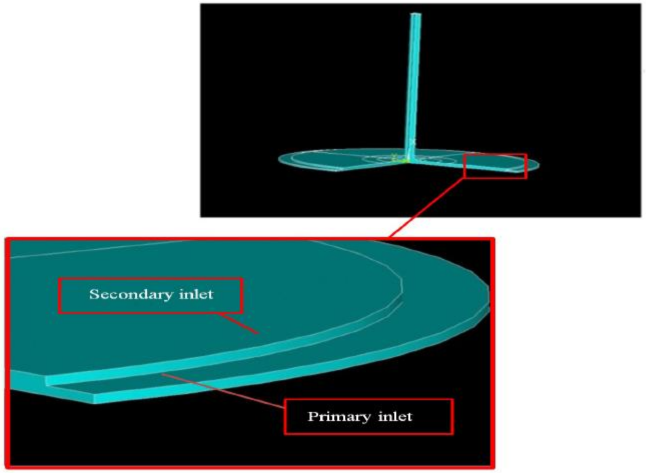


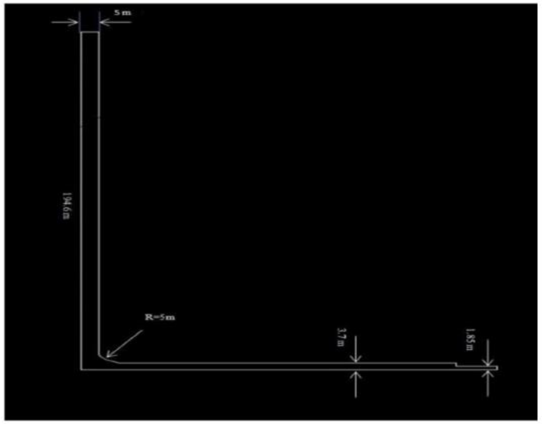


Double-Inlet Collector









Analytical Approach

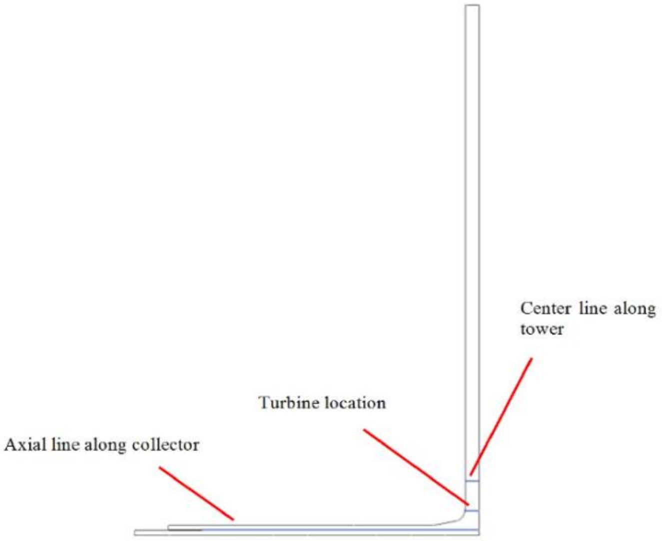
$$\dot{m}_{i_2} = 2\pi r(h_{c,i_2} - h_{c,i_1})u_{i_2}$$

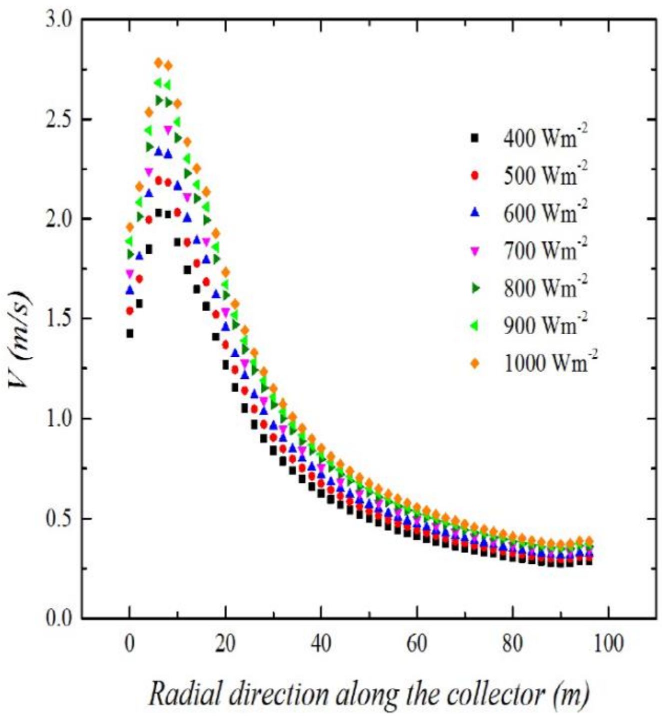
$$u_{i_2} = u_{ref}(\frac{h_{c,i_2}}{h_{ref}})^{\alpha}$$

$$\alpha = 1/ln(h_{ref}/h)$$

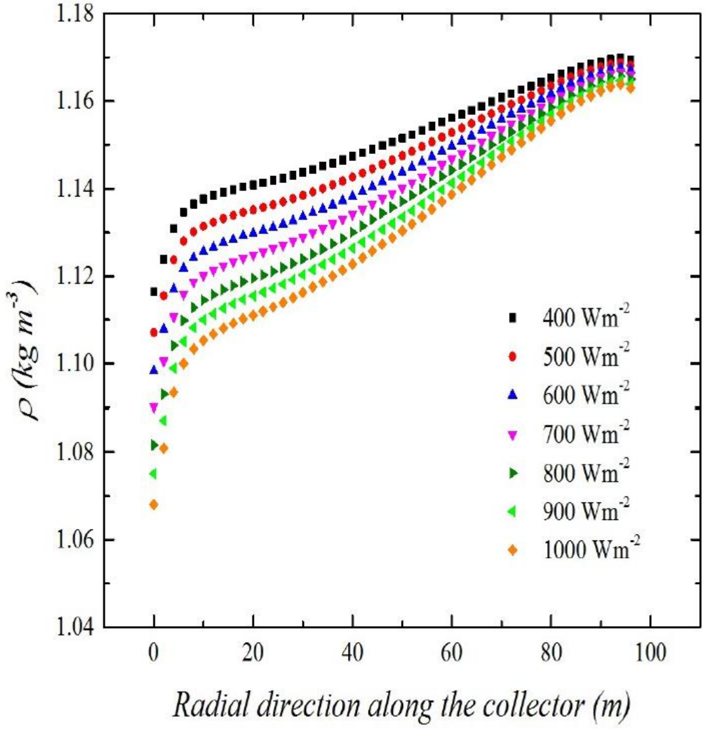
u_{ref} is the wind velocity measured at h_{ref} which is considered as the reference wind velocity value, and α is the wind shear exponent.

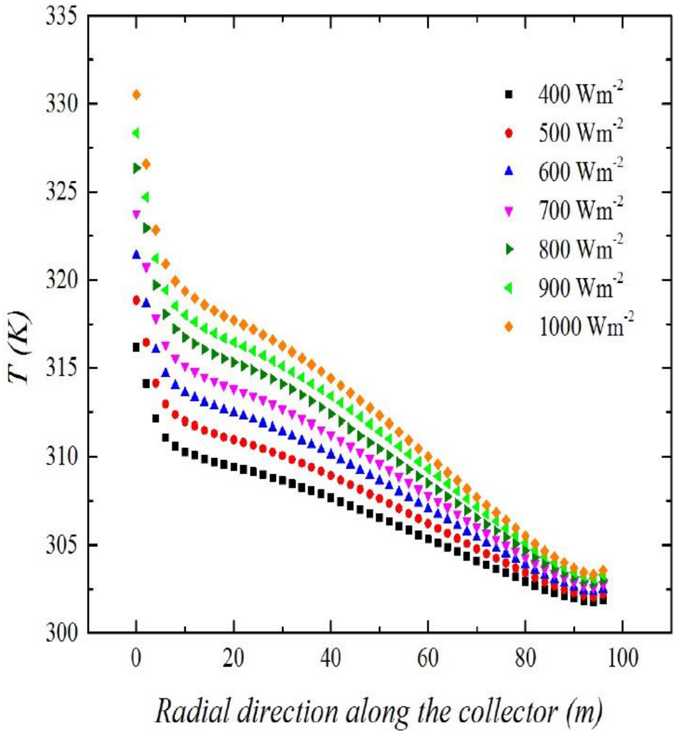
Double-Inlet Collector Numerical Analysis



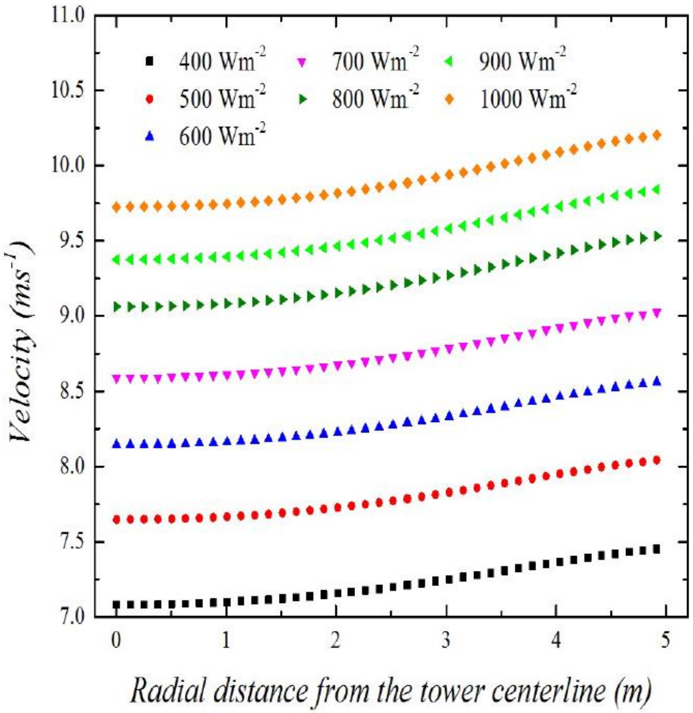


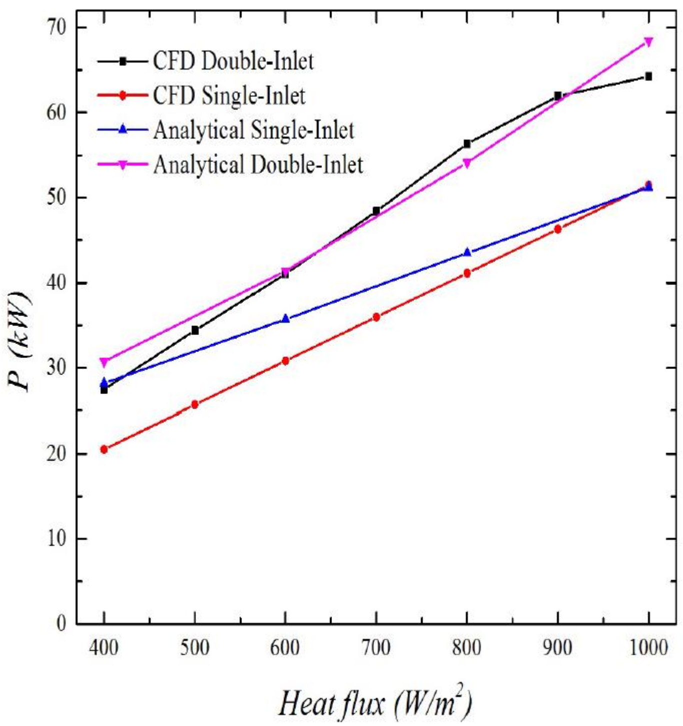
Numerical Analysis





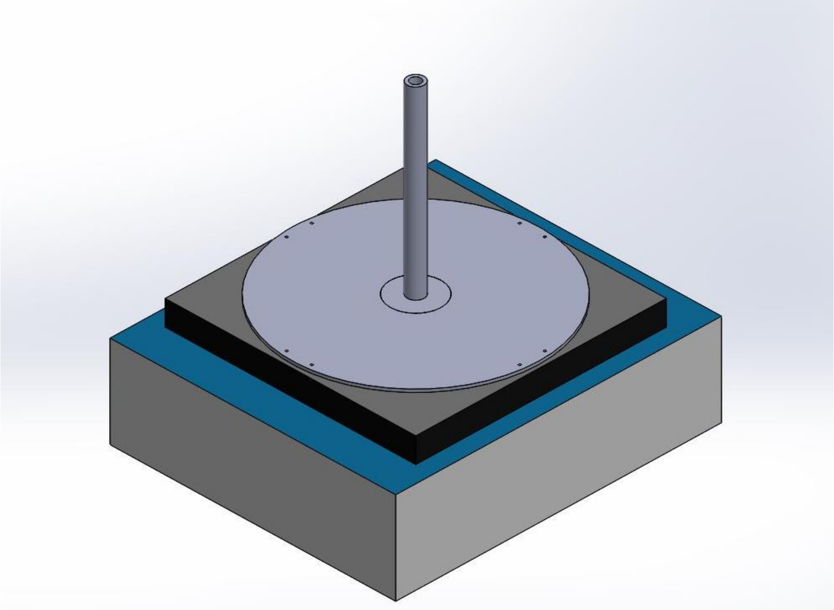
Numerical Analysis



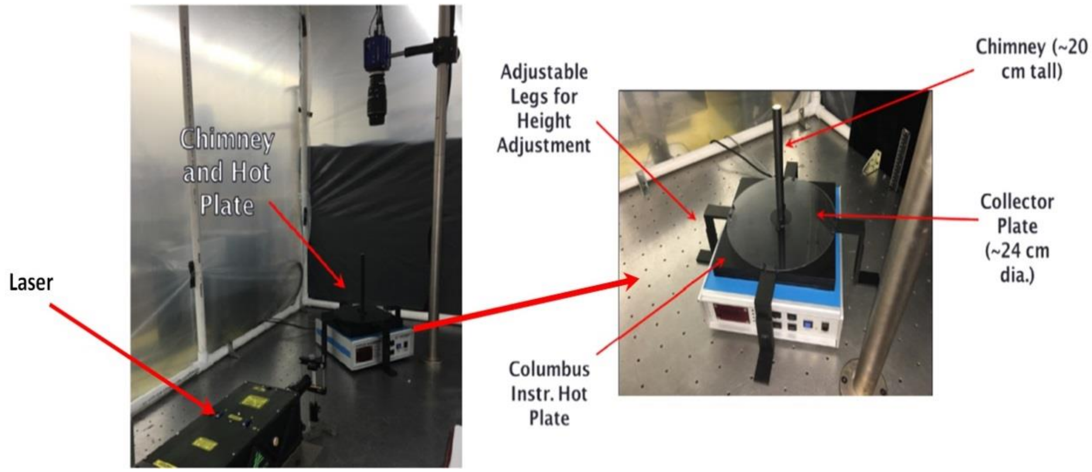


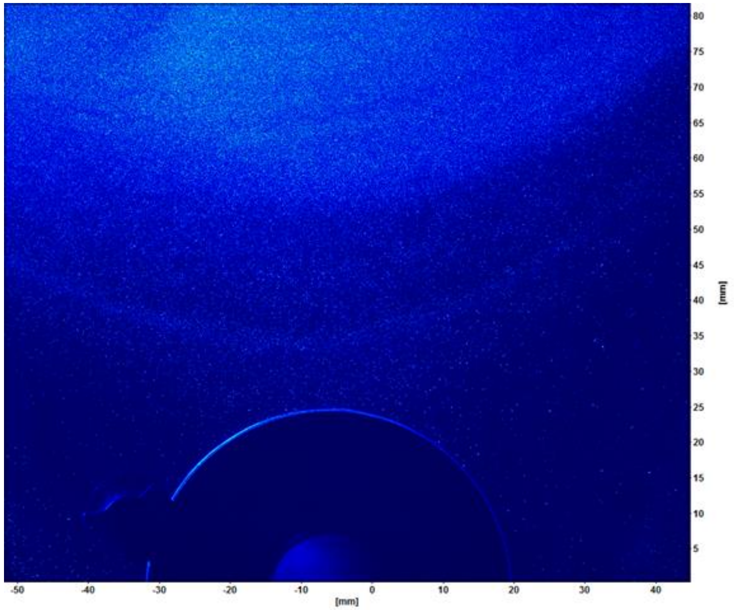
Experiments

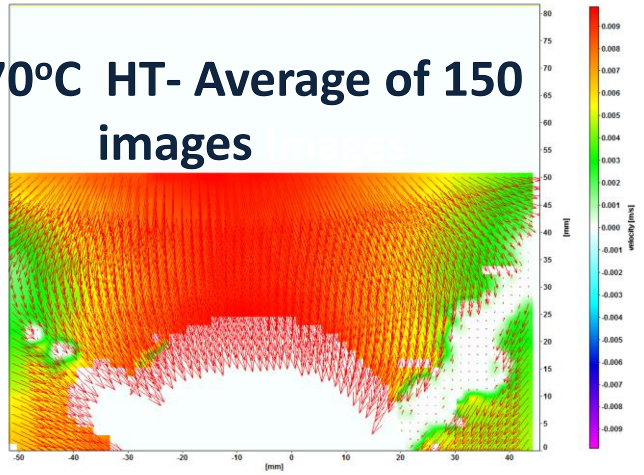
"A computer lets you make more mistakes faster than any invention in human history— with the possible exceptions of handguns and tequila."- Mitch Ratcliffe



Experimental Analysis







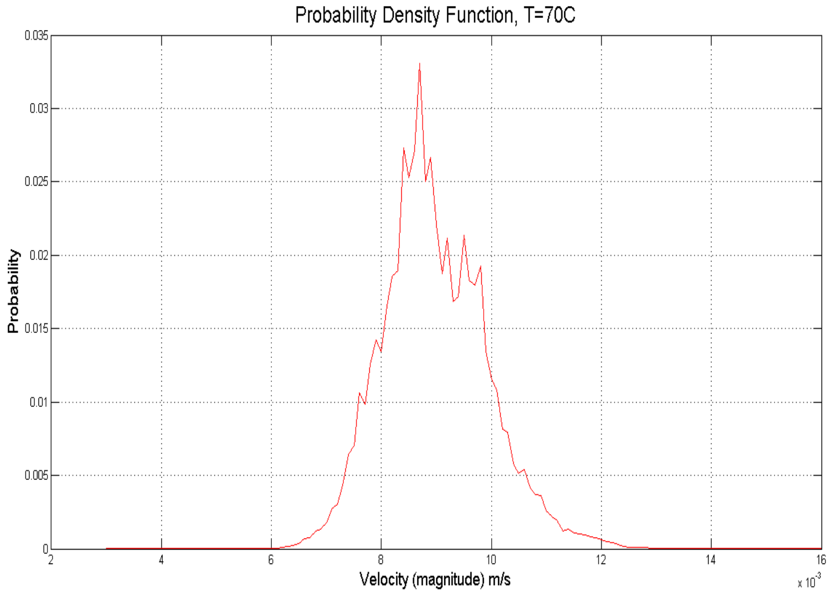
$70^{o}C$ HT- Average of 150 images

Experimental Results

- Mean:

  u=9.01 mm/s

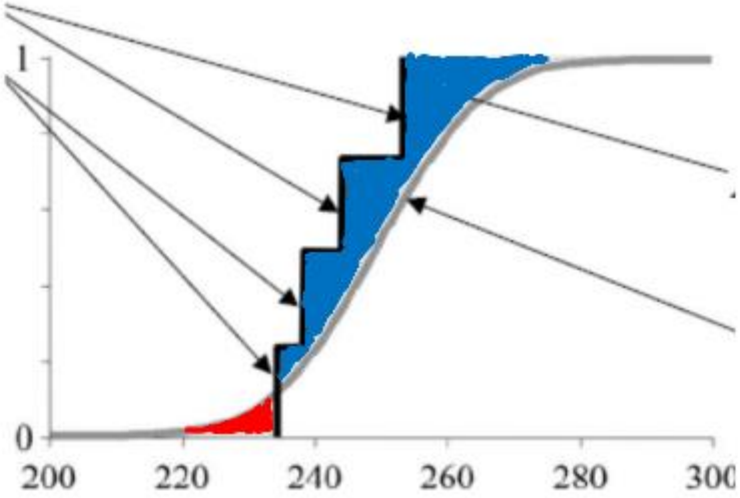
$$u \in [7.21, 10.7]\frac{mm}{s}$$



Examples of the Area Validation Metric

- ►The modified form for CDF has a separate tracking
  - ►Experiments larger than simulation, d^+
  - ►Experiments smaller than simulation, d^-

$$[S + F_s\, d^-, S + F_s d^+] \text{ where } F_s = 1.25$$

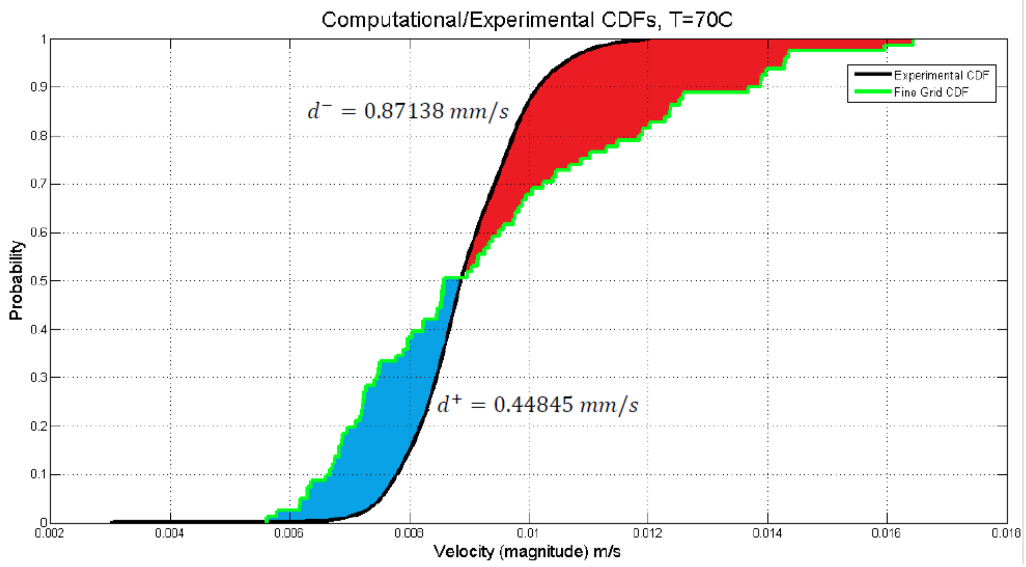


Mismatch Representation

We can represent the model form uncertainty in an interval by having the mismatch.

- $u_{model} = [S - F_s d^-, S - F_s d^+] \frac{mm}{s} = [8.15, 10.3] \frac{mm}{s}$
- S is the simulation results
- d represents the mismatch

The **validation metric** **is defined to be the area between the EDF/CDF from the simulation and the EDF/CDF from the experiment.**



Model Verification

- Observed order of accuracy: $\widehat{p} = 1.043$

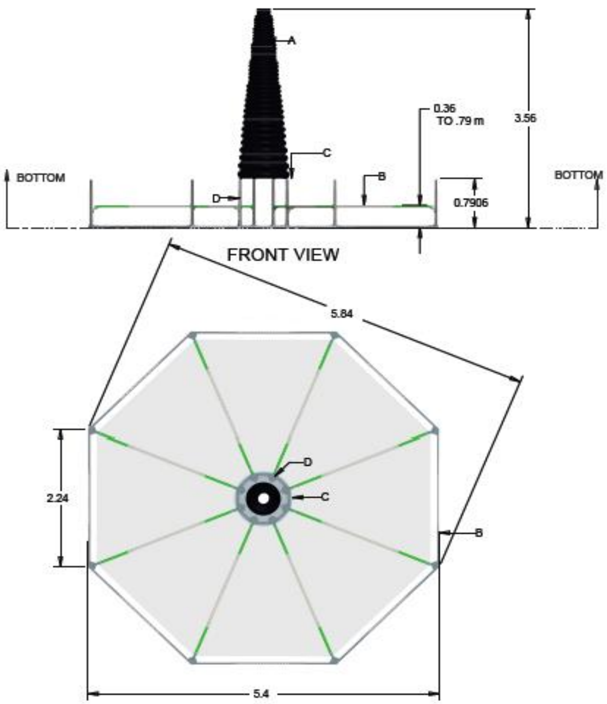
$$\hat{p} = \frac{\ln\left(\frac{f_3 - f_2}{f_2 - f_1}\right)}{\ln(r)} \qquad r = \frac{h_2}{h_1} = \frac{h_3}{h_2}$$

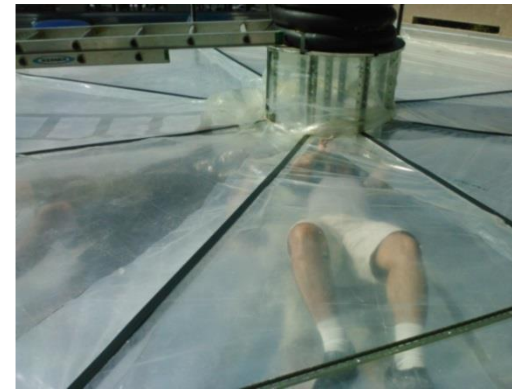
- Estimated exact solution (RE): $\bar{u}$ =10.508 mm/s
- Estimated DE: $\varepsilon_h = 0.1154$ mm/s

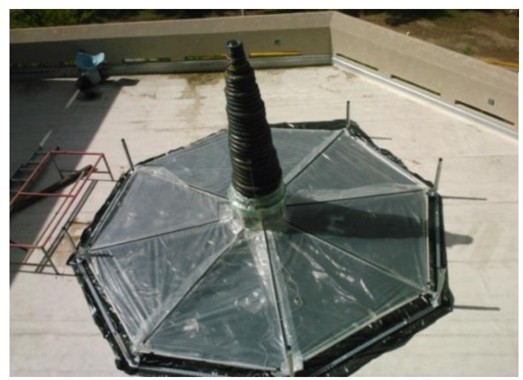
$$\varepsilon_h \cong u_h - \overline{u}$$

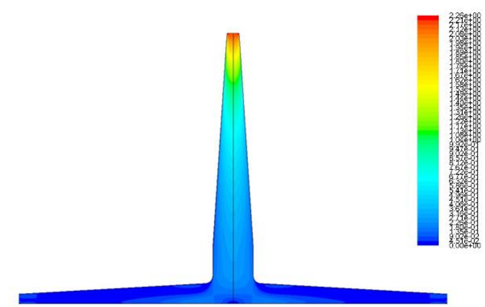
- Grid Convergence Index: $GCI = 0.3463$ mm/s

Inflatable Tower

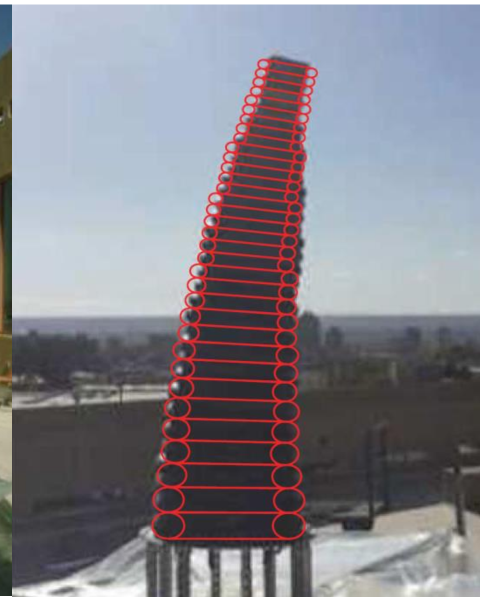








Inflatable Tower

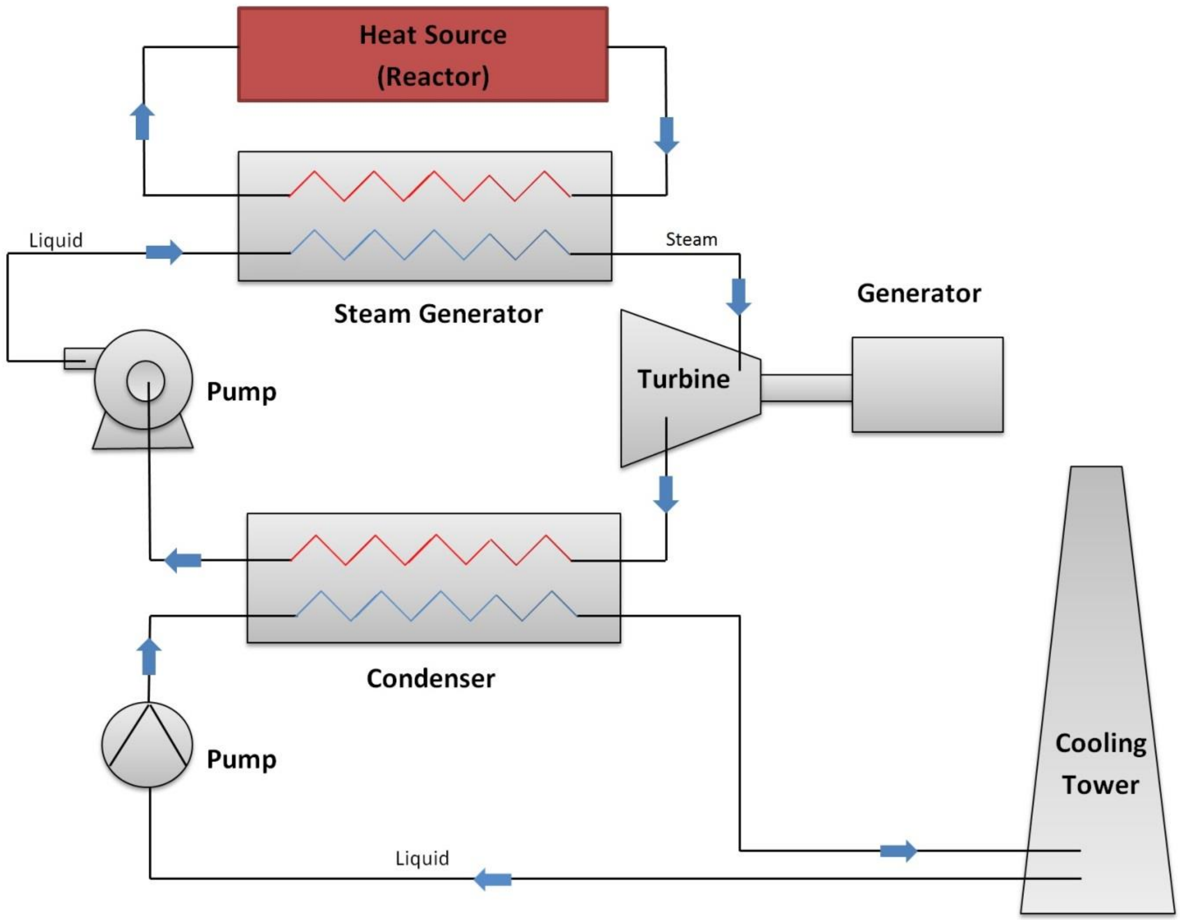


2 m/s

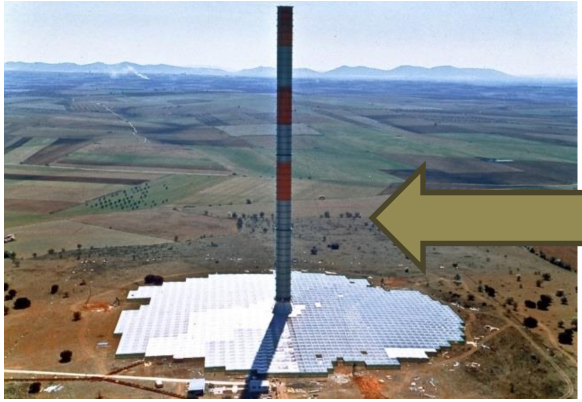
15 m/s

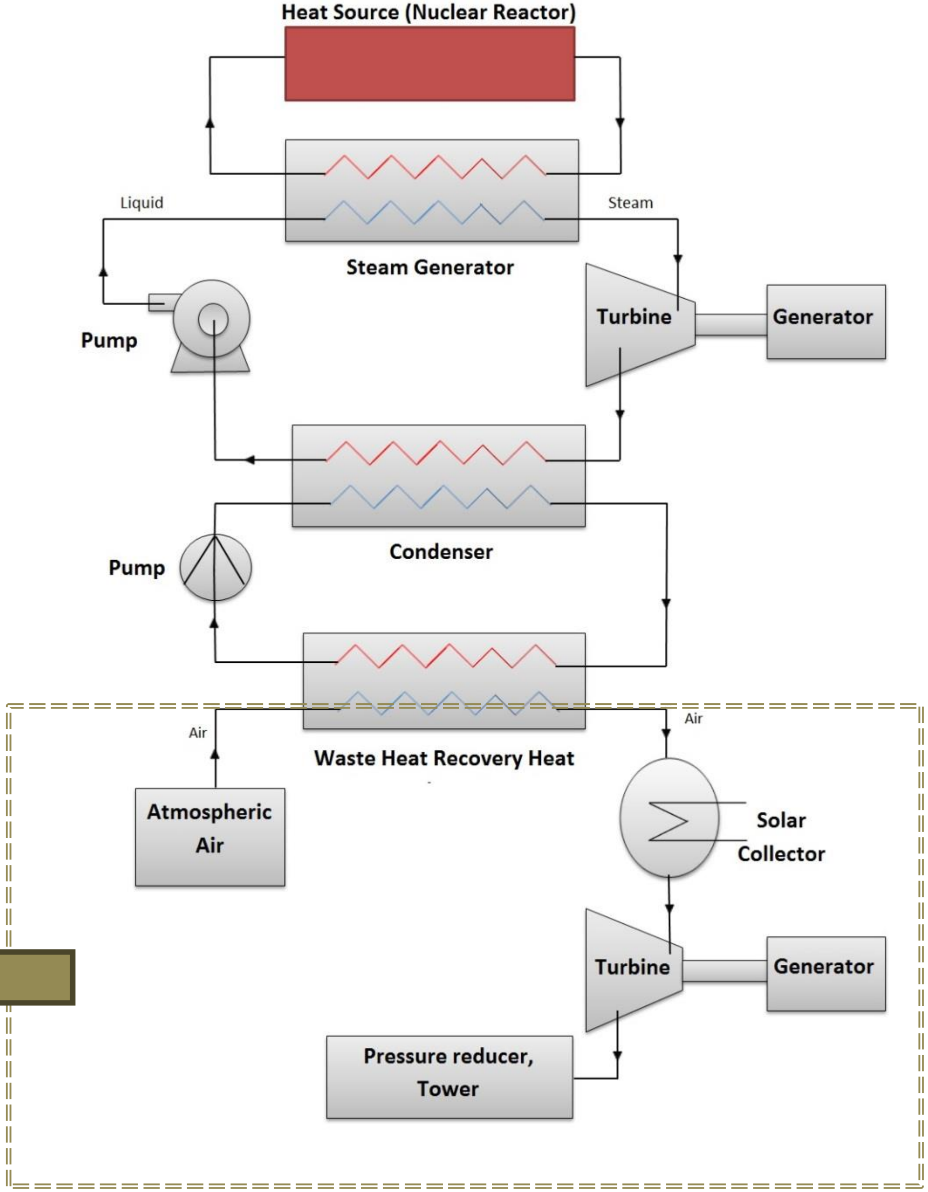
Combined Cycle

Thermal Cycle of a PWR

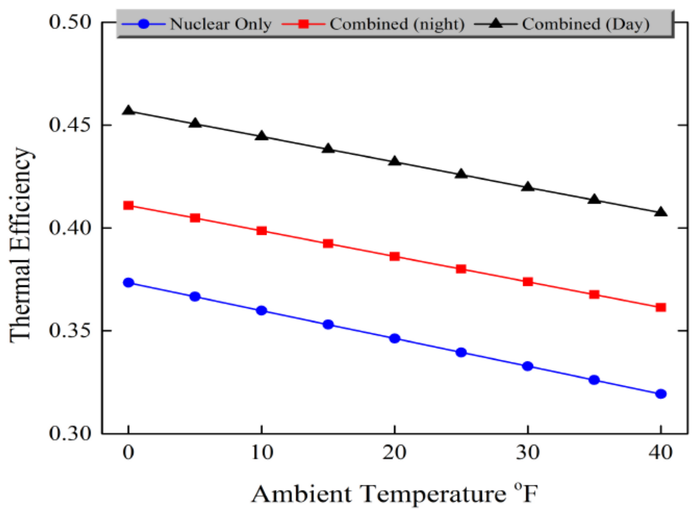


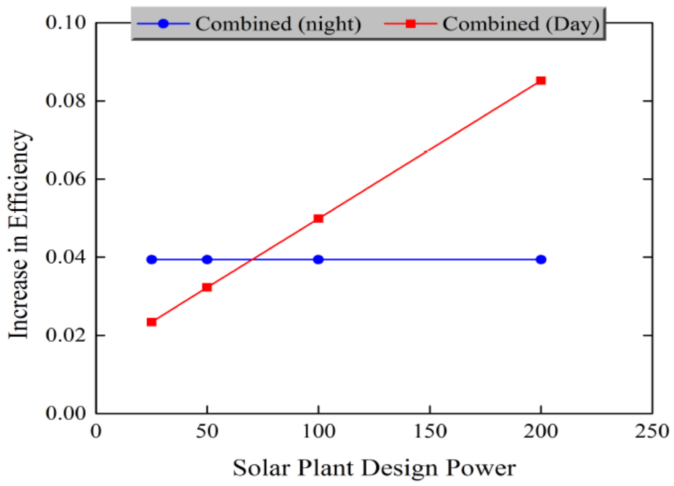
The Proposed Cycle

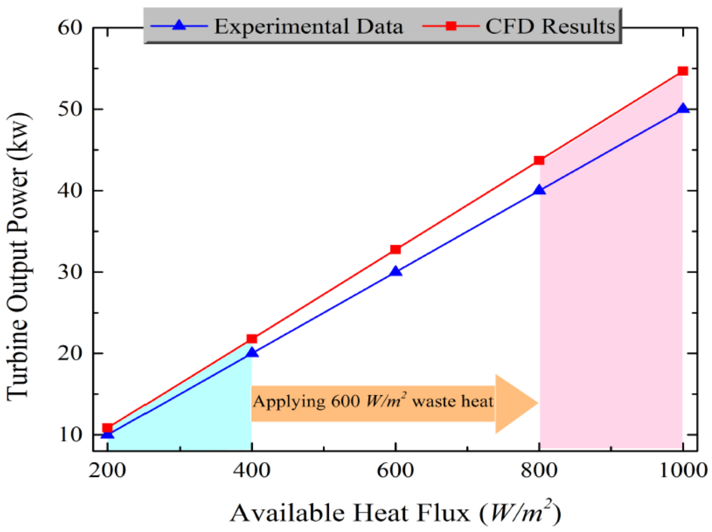




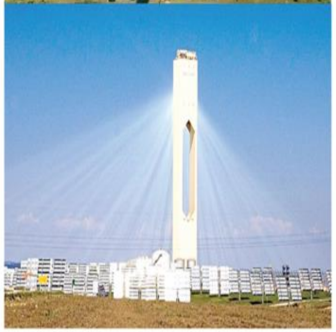
Combined Solar Cycle

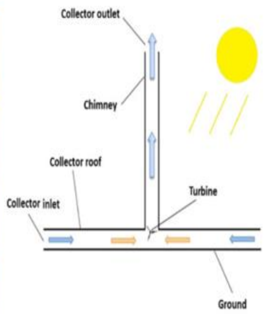


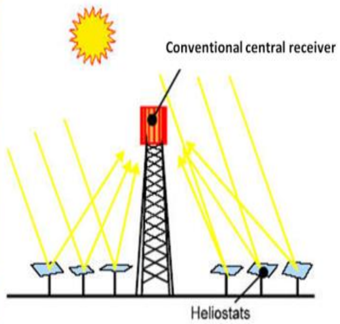


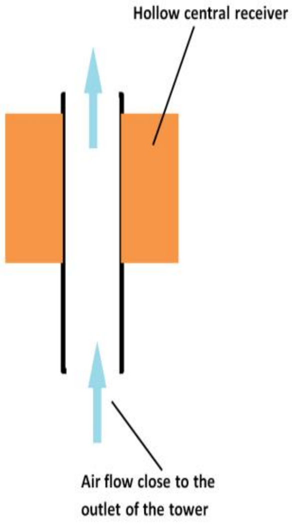


On going work









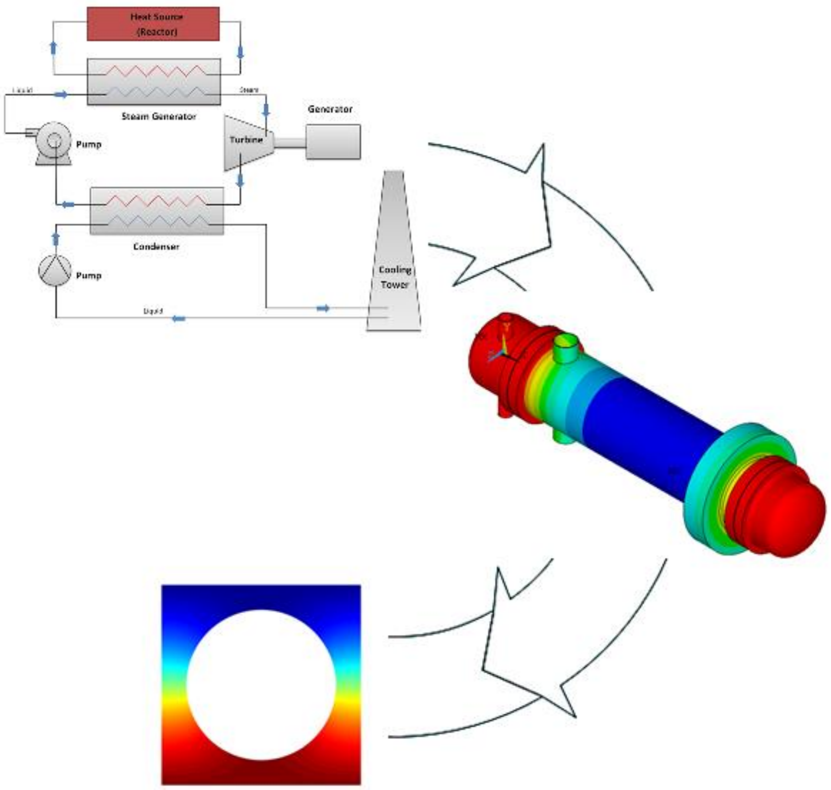
Optimal collector shape: roof and ground*

Heat waste recovery**

*Will be presented at the next ☺ PIMS Workshop on Mathematical Sciences and Clean Energy Applications

** Sponsored by Compo Energy

Heat Exchanger



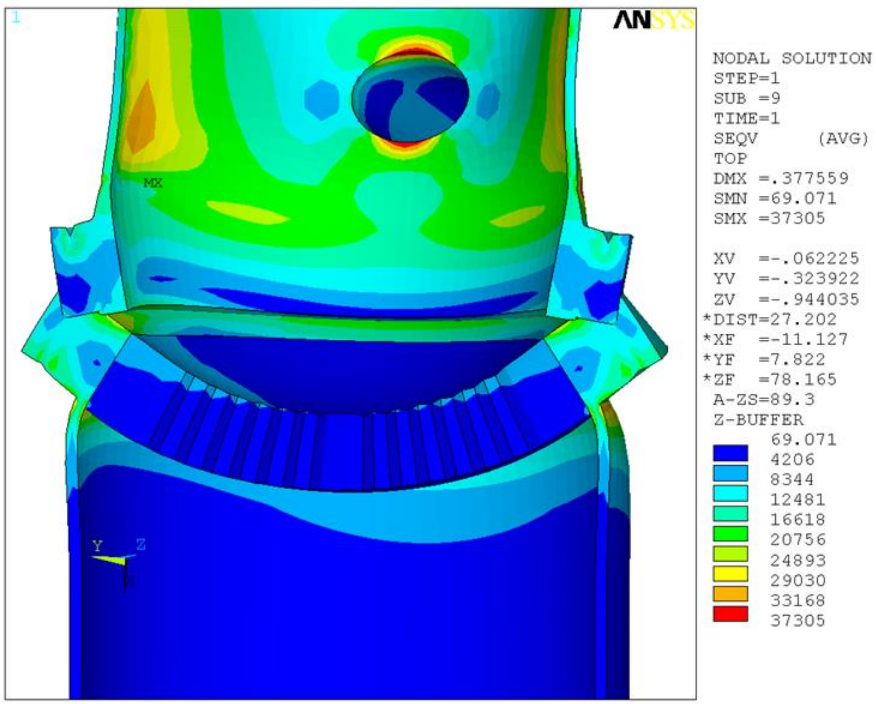
Heat exchanger is a key component in any thermal power cycle. Thermal design and numerical model especially for high temperature and pressure applications

Computational and experimental inspection and testing per ASME codes

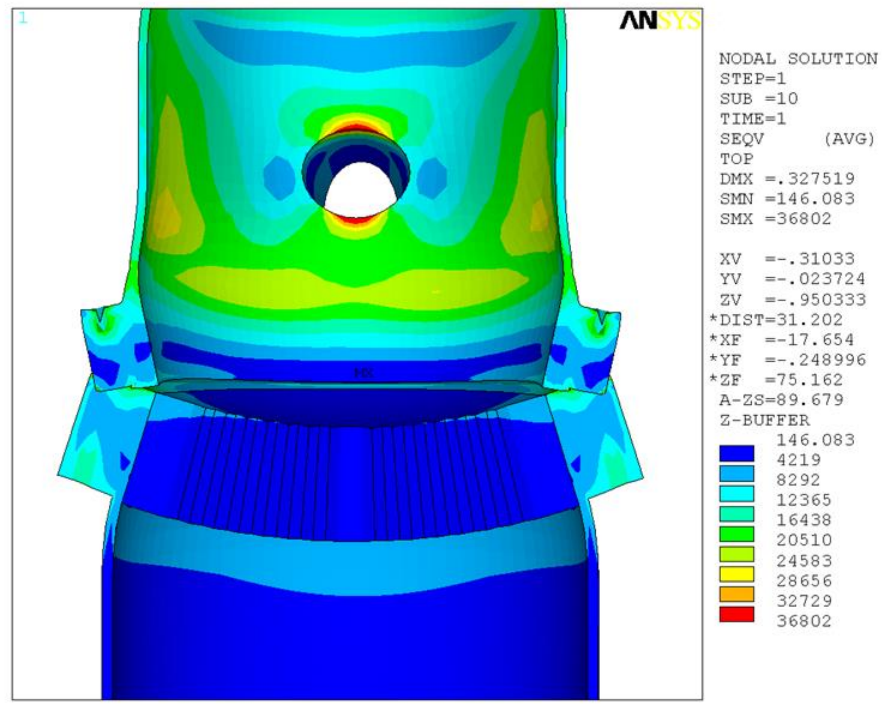
Propose enhancement in thermal-hydraulics performance of HX

Involving advanced manufacturing to fabricate

Excessive distortion of tubesheet due to temperature differential



Initial design
(T.S. 4 7/8") (150X magnification)

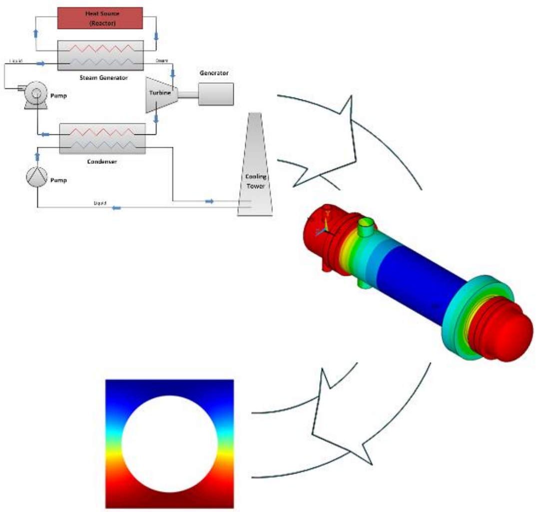


Final Design
(T.S. 8") (150X magnification)

Thermal Response

Important aspect in HX for inspection and testing

- Cladding
- Thermal fatigue
- Porous composite

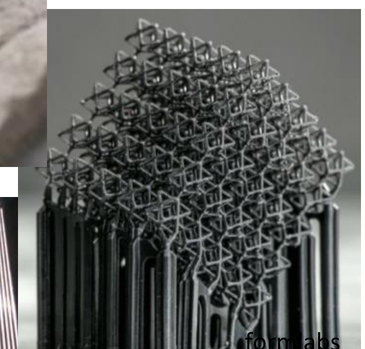


Effective thermal material properties of the applied composite shall be evaluated

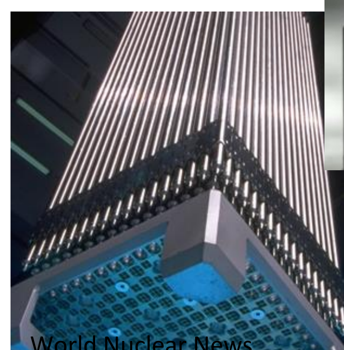
More Applications

- Porous media
  - Materials & structures containing voids of different phases
- Examples
  - Aerogels
  - 3D-printed structures
  - Nuclear fuel assemblies
  - Carbon composites
  - Pipelines

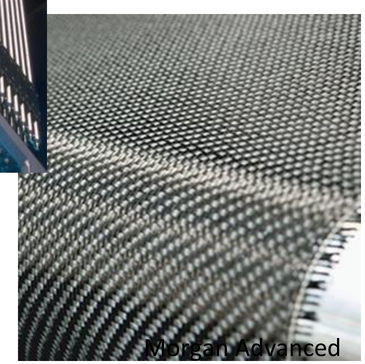
Aspen Aerogels



formlabs

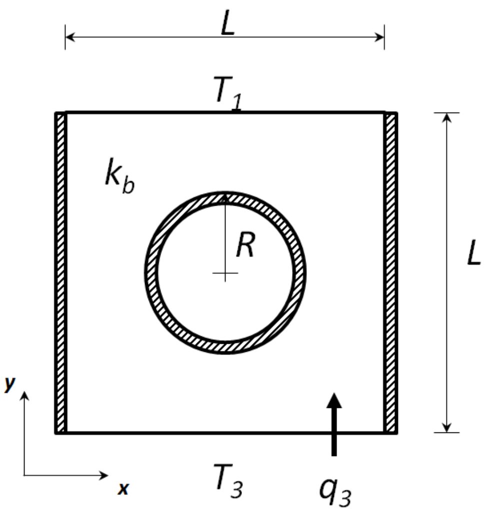


World Nuclear News



Morgan Advanced Materials

Computational Model

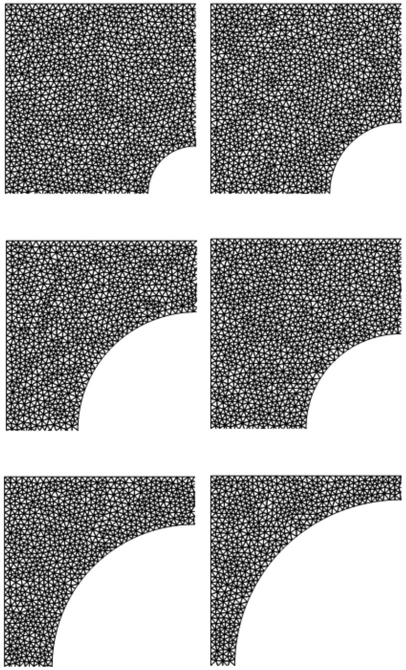


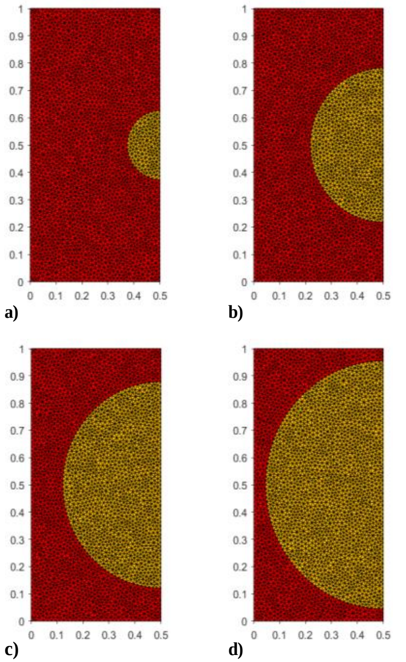
Unit Cell Structure

k_b = bulk thermal conductivity
k^* = dimensionless effective thermal conductivity
L = cell length & width
q = heat flux
R = void radius
T = temperature
α = porosity

$$\alpha = \frac{\pi R^2}{L^2}$$

$$k^* = \frac{q_3 L}{k_b (T_3 - T_1)}$$





Code Verification

Method of Manufactured Solutions (MMS)

Solution

$$T_{MMS(x,y)} = \cos(x\pi/L)\ \sin(y\pi/L+0.75)$$

Source Term

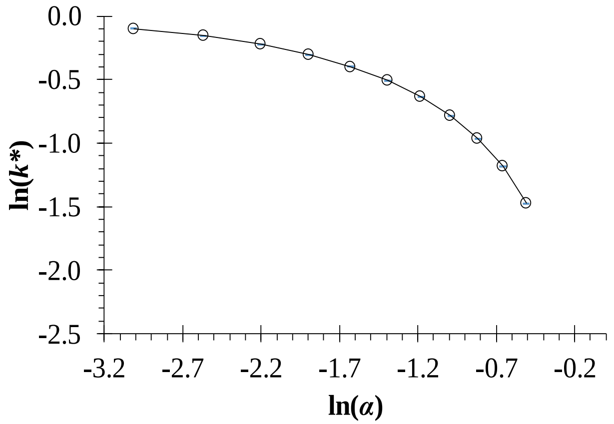
$$Q_{MMS}(x,y)=(k_x)\cos\left(\frac{x\pi}{L}\right)\sin\left(\frac{y\pi}{L}+0.75\right)\frac{\pi^2}{L^2}$$

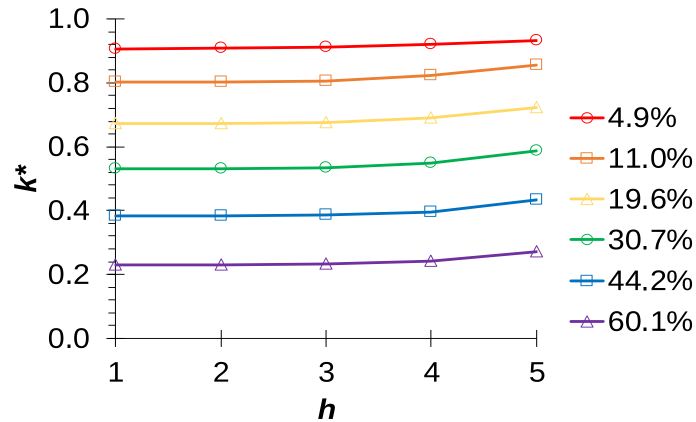
Error

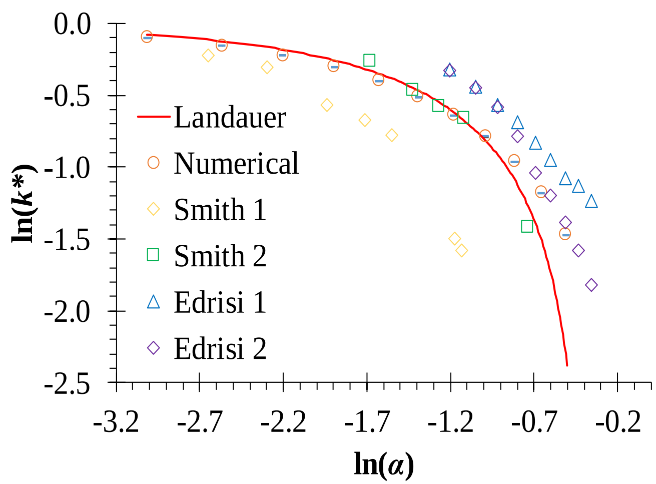
$$\epsilon_h=\sqrt{\Sigma_{i=1}^{N_v}\left[T_i-T_{MMS}(x_i,y_i)\right]^2/N_v}$$

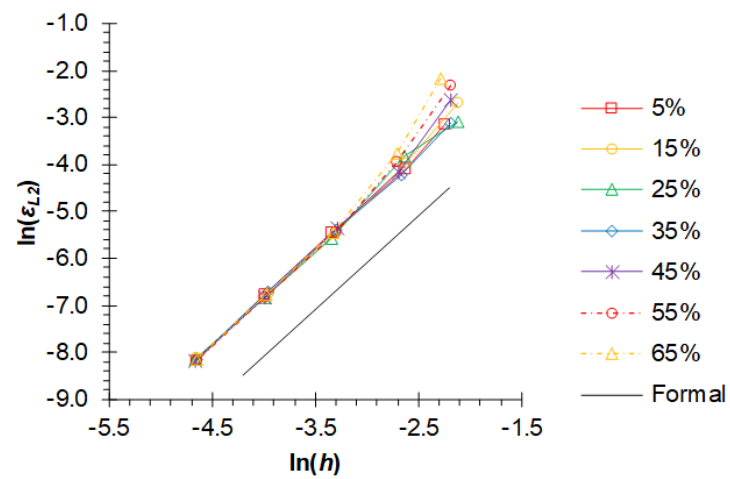
α	k^*	k^*_{ext}	p	ε_a	ε_{ext}	GCI	$U_{num,1}$	$U_{num,2}$
%	---	---	---	%	%	%	---	---
4.9	0.91	0.91	1.55	0.14	0.08	0.10	0.0009	0.0019
7.7	0.86	0.86	1.92	0.15	0.05	0.07	0.0006	0.0007
11.0	0.80	0.80	1.68	0.15	0.07	0.09	0.0007	0.0014
15.0	0.74	0.74	1.82	0.15	0.06	0.07	0.0005	0.0009
19.6	0.67	0.67	2.09	0.15	0.05	0.06	0.0004	0.0006
24.9	0.60	0.60	1.98	0.15	0.05	0.07	0.0004	0.0004
30.7	0.53	0.53	2.14	0.16	0.05	0.06	0.0003	0.0007
37.1	0.46	0.46	1.94	0.18	0.06	0.08	0.0004	0.0004
44.2	0.38	0.38	2.06	0.20	0.06	0.08	0.0003	0.0004
51.8	0.31	0.31	2.22	0.23	0.07	0.08	0.0003	0.0007
60.1	0.23	0.23	1.90	0.30	0.11	0.14	0.0003	0.0005

Some Results



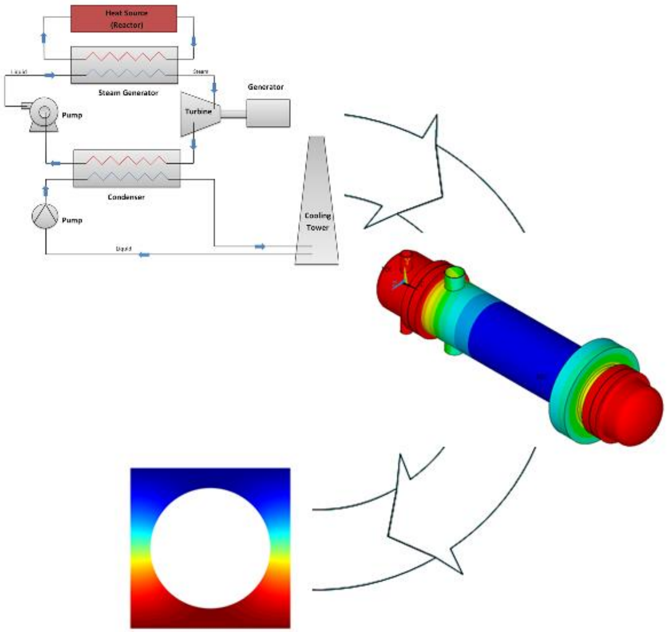






Summary

- **Hybrid clean energy systems can be a solution to provide a more stable baseline of energy**
- **Design, development and modeling advanced hybrid clean energy power cycle are presented**
- **Computational fluid dynamics and heat transfer evaluation of energy conversion components**
- **Experimental prototype analysis was performed to validate our numerical model**



References

Irick, Kevin, and Nima Fathi. “Computational Evaluation of Thermal Barrier Coatings: Two-phase Thermal Transport Analysis.” In ASME Verification and Validation Symposium Transaction, 2019 (accepted).

Aleyasin, Seyed Sobhan, Nima Fathi, Mark Francis Tachie, Peter Vorobieff, and Mikhail Koupriyanov. "On the development of incompressible round and equilateral triangular jets due to Reynolds number variation." Journal of Fluids Engineering 140, no. 11 (2018): 111202.

Irick, Kevin*, and Nima Fathi. "Thermal Response of Open-Cell Porous Materials: A Numerical Study and Model Assessment." In ASME 2018 Verification and Validation Symposium, pp. V001T03A002-V001T03A002. American Society of Mechanical Engineers, 2018.

Fathi, Nima, Patrick McDaniel, Seyed Sobhan Aleyasin, Matthew Robinson, Peter Vorobieff, Salvador Rodriguez, and Cassiano de Oliveira. "Efficiency enhancement of solar chimney power plant by use of waste heat from nuclear power plant." Journal of Cleaner Production 180 (2018): 407–416

N. Fathi, S.S. Aleyasin, P. Wayne, P. Vorobieff, “Computational Assessment of Double- Inlet Collector in Solar Chimney Power Plant Systems, ASME Fluids Engineering Division FEDSM 2017

S.S. Aleyasin, N. Fathi, M. Tachie, P. Vorobieff and M. Koupriyanov , “Experimental- Numerical Analysis of Turbulent Incompressible Isothermal Jets” , ASME FEDSM 2017

S.S. Aleyasin, N. Fathi, M. Tachie, and M. Koupriyanov, “Comparison of Turbulent Jets Issuing from Various Sharp Contoured Nozzles”, ASME FEDSM 2017

N. Fathi, P. McDaniel, C. Forsberg, C. de Oliveira, “ Power Cycle Assessment of Nuclear Systems, Providing Energy Storage for Low Carbon Grids,“ Journal of Nuclear Engineering and Radiation Science, published online, Sep, 2017

N. Fathi, P. McDaniel, C. Forsberg and C. de Oliveira, “Nuclear Systems for a Low Carbon Electrical Grid.”ASME ICONE24, Jun. 2016

N. Fathi, S. S. Aleyasin, P. Vorobieff, “Numerical-Analytical Assessment on Manzanares Prototype” Journal of Applied Thermal Engineering, Accepted, (3-25-16)

Aleyasin, Seyed Sobhan, Nima Fathi, and Peter Vorobieff. "Experimental Study of the Type VI Stilling Basin Performance," Journal of Fluids Engineering 137, no. 3 (2015): 034503.

Fathi, Nima, Keith Mertens, Vakhtang Putkaradze, and Peter Vorobieff. "Comment on “The role of wetting heterogeneities in the meandering instability of a partial wetting rivulet” by Couvreur S. and Daerr A." EPL (Europhysics Letters) 108, no. 5 (2014)

Putkaradze, Vakhtang, Peter Vorobieff, Andrea Mammoli, and Nima Fathi. "Inflatable free- standing flexible solar towers," Solar Energy 98 (2013): 85-98

Vorobieff, Peter V., Nima Fathi, Andrea A. Mammoli, Vakhtang Putkaradze, Michael Chi, Seyed Sobhan Aleyasin, and Francois Gay-balmaz. "Inflatable, free-standing solar updraft tower with optimal geometry and active control." U.S. Patent Application 14/879,398, filed June 26, 2018.

“Multi-Source Sustainable-Renewable Energy Harvester”, Nima Fathi, Peter Vorobieff, Pat McDaniel, Seyed Sobhan Aleyasin, application filed with STC at UNM, Track Code: 2019-061

Thank you!
Questions?

nfathi@unm.edu