V&V Exercise for a Solar Tower Power Plant

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Evaluation and Enhancement of Solar Chimney Power Plant

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Outline

• Background and Motivation
• Analytical Study
• Double-Inlet Collector
• Inflatable Tower
• Combined Solar Cycle
Solar Chimney Power Plant
Background

• 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.
Manzanares Prototype

<table>
<thead>
<tr>
<th>Prototype component</th>
<th>Size (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean collector radius</td>
<td>122.00</td>
</tr>
<tr>
<td>Collector height</td>
<td>1.85</td>
</tr>
<tr>
<td>Chimney radius</td>
<td>5.08</td>
</tr>
<tr>
<td>Chimney height</td>
<td>196</td>
</tr>
<tr>
<td>Rotor blade length</td>
<td>5</td>
</tr>
</tbody>
</table>
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)

• The efficiency of solar systems are still low, especially solar chimney power plants.
Motivation

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 0.9% in 2016.
Analytical Study

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

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

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

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

\[ \dot{W} \approx \dot{m} (p_{c,o} - p_{t,i}) \]

\[ \rho_{turb} \]
Analytical Study-Collector

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

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

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

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

\[ p_{t,o} - p_{t,i} \simeq -\rho_{m,t} gh_t - \frac{\dot{m}^2}{2\rho_{m,t}} \left( \frac{1}{A_{t,o}^2} - \frac{1}{A_{t,i}^2} \right) \]
Analytical Study - Power Calc

\[ \dot{W} \approx \frac{\dot{m}(p_{c,o} - p_{t,i})}{\rho_{turb}} \]

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

- Turbulent Flow
- Air
- Natural Convection
Computational Study

Applied boundary conditions
Computational Study

Velocity contour plot, m/s
Comparative Study - Evaluation
Analytical Power

![Graph showing the relationship between mass flowrate (kg/sec) and output power (kW) for different solar irradiances and updraft velocities.]

- Solar Irradiation (W/m²)
  - 200
  - 400
  - 600
  - 800
  - 1000

- Output Power (kW)
  - 51.2 kW
  - 51.8 kW

- 9 m/s updraft velocity as the maximum reported value

![Graph showing the relationship between mass flowrate (kg/sec) and output power (kW) for different efficiencies (ηc).]
Double-Inlet Collector
Double-Inlet Collector
Analytical Approach

\[ \dot{m}_{i2} = 2\pi r (h_{c,i2} - h_{c,i1}) u_{i2} \]

\[ u_{i2} = u_{ref} \left( \frac{h_{c,i2}}{h_{ref}} \right)^\alpha \]

\[ \alpha = \frac{1}{\ln(h_{ref}/h)} \]

\( u_{ref} \) is the wind velocity measured at \( h_{ref} \) which is considered as the reference wind velocity value, and \( \alpha \) is the wind shear exponent.
Double-Inlet Collector Numerical Analysis
Numerical Analysis
Numerical Analysis
New Experiments
Experimental Analysis

• Why do we need these experiments?

• How should we evaluate our analysis based on the mathematical model used in our simulation?

• How to measure the fidelity of our numerical work against experimental analysis?
Credibility in Scientific Computing

- Verification and Validation activities

  - **Verification** is the process of assessing **software correctness** and **numerical accuracy** of the solution to a given mathematical model.

  - **Validation** is the process of assessing the **physical accuracy** of a mathematical model based on **comparisons** between **computational** results and **experimental** data.
V&V

- Verification and Validation (V&V) are the primary processes for assessing and quantifying the accuracy of computational results.

- What should be perspective of V&V?
  - Skepticism, sometimes to the degree of being radical (Tetlock, 2005)
V&V

- In **verification**, the association or relationship of the simulation to the real world is **NOT** an issue.

- In **validation**, the relationship between the mathematical model and the **real world** is the issue.
One of the main people in this field:

Dr. Patrick J. Roache's primary area of expertise is in the numerical solution of partial differential equations, particularly those of fluid dynamics, heat transfer, and electrodynamics, with special interest in Verification and Validation. He is the author of the original (1972) CFD book Computational Fluid Dynamics (translated into Japanese, Russian, and Chinese), the monograph Elliptic Marching Methods and Domain Decomposition (1995), the widely referenced Verification and Validation in Computational Science and Engineering (1995), the successor to the original CFD book Fundamentals of Computational Fluid Dynamics (1995), the successor to the original V&V book Fundamentals of Verification and Validation (2009), and the booklet A Defense of Computational Physic (2012) [ASME 2012 V&V symposium biography].
Experimental Analysis
Experimental Analysis
Experimental Analysis

70°C HT - Average of 150 images

Vectors enlarged to show directional flow
Experimental Results

- Mean:
  \[ u = 9.01 \text{ mm/s} \]

- 95% Confidence interval:
  \[ u \in [7.21, 10.7] \frac{mm}{s} \]
Model Verification

- Observed order of accuracy: \( \hat{p} = 1.043 \)

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

- Estimated exact solution (RE): \( \bar{u} = 10.508 \text{ mm/s} \)

- Estimated DE: \( \varepsilon_h = 0.1154 \text{ mm/s} \)

\[
\varepsilon_h \approx u_h - \bar{u}
\]

- Grid Convergence Index: \( GCI = 0.3463 \text{ mm/s} \)
Examples of the Area Validation Metric

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

$$[S + F_s d^-, S + F_s d^+]$$ where $F_s = 1.25$
Validation Metric—Mismatch Representation

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

\[ d^- = 0.87138 \text{ mm/s} \]

\[ d^+ = 0.44845 \text{ mm/s} \]
**Uncertainty Representation**

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

- \( u_{model} = \left[ S - F_s d^-, S - F_s d^+ \right] \frac{mm}{s} = [8.15, 10.3] \frac{mm}{s} \)

- \( S \) is the simulation results

- \( d \) represents the mismatch
Older works: Inflatable Tower
Older works: Inflatable Tower

2 m/s

15 m/s
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 States 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.
Combined Nuclear-Solar Thermal Cycle of a PWR
Combined Nuclear-Solar
The Proposed Cycle
Combined Nuclear-Solar

- Left graph: Thermal Efficiency vs. Ambient Temperature (°F)
  - Nuclear Only
  - Combined (night)
  - Combined (Day)

- Right graph: Increase in Efficiency vs. Solar Plant Design Power
  - Combined (night)
  - Combined (Day)
Combined Nuclear-Solar
Conclusion

• SCPP was studied analytically and numerically and the results were compared against the available experimental values.

• Several modifications were considered to increase the efficiency of the power plant.

• Experimental prototype analysis was performed to validate our numerical model and helped us to modify our model.

• Combined cycle approach for this air Brayton cycle is highly suggested and other types of modifications should be considered.
References


Thank you!

Questions?