Improved Heat Transfer Correlation for Large Scale Solar PV Convection Modeling

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As module temperatures rise, efficiency drops and degradation accelerates. Can reduce power output by ~12%.

Pathways for mitigating thermal losses in solar photovoltaics

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Energy balance of PV module

\[ Q_{\text{conv}} = h \cdot (T_{\text{front/back}} - T_{\text{amb}}) \]

\[ Q_{\text{rad}} = f(T_{\text{rad. prop.}}, T_{\text{front/back}}, T_e, T_{\text{sky}}) \]

\( h \) = convective heat transfer coefficient
Sources of thermal losses in solar PV

\[ q_{rad} + q_{conv} = q_{sun} - q_{refl} - P(T) \]

where:

\[ P(T) = P_{STC} \left[ 1 + \beta(T - T_{STC}) \right] \]

\[ q_{refl} = q_{refl}^{sup} + q_{refl}^{sub} \]

\[ q_{conv}(T) = h(T - T_{\infty}) \]

\[ T = \frac{hT_{\infty} + q_{sun} - q_{refl} - q_{rad}(T) - P_{STC}(1 - \beta_p T_{STC})}{h + \beta_p P_{STC}} \]

Vaillon et al. 2018, Nature Scientific Reports
Increasing convective heat transfer can increase power output

Increasing $h$ by 50% can lead to an increase in power of 6%

Solar PV has a strong non-linear relation with convective cooling!

$P - P_0$ [%] vs. $h/h_0$

$h = \text{convective heat transfer coefficient}$

Vaillon et al. 2018, Nature Scientific Reports
Module temperature strongly depends on local wind velocity

Griffith et al. 1981
Existing relationships for $h$ neglect important factors

<table>
<thead>
<tr>
<th>Authors</th>
<th>Location of the velocity ($V$) measurement</th>
<th>Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sparrow and Tien [15]</td>
<td>Free stream</td>
<td>$(h/pC_pV)^{2/3} = 0.931 \text{Re}^{-1/2}$</td>
</tr>
<tr>
<td>Sparrow et al. [16]</td>
<td>Free stream</td>
<td>$(h/pC_pV)^{2/3} = 0.86 \text{Re}^{-1/2}$</td>
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<tr>
<td>Test et al. [42]</td>
<td>1 m above the plate</td>
<td>$h = 2.56V + 8.55$</td>
</tr>
<tr>
<td>Kind et al. [43]</td>
<td>14 cm above the tunnel floor</td>
<td>$h/pC_pV = f(\text{Re})$ presented graphically</td>
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<tr>
<td>Shakerin [45]</td>
<td>Average near model</td>
<td>$(h/pC_pV)^{2/3} = 1.23\text{Re}^{-1/2}$, $\alpha &lt; 40$ deg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$(h/pC_pV)^{2/3} = 0.90\text{Re}^{-1/2}$, $\alpha \geq 40$ deg</td>
</tr>
<tr>
<td>Onur [46]</td>
<td>Not available</td>
<td>$\text{Nu} = 0.568 \text{Re}^{0.54}$ Roof inclination 30 deg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\text{Nu} = 1.067 \text{Re}^{0.466}$ Roof inclination 45 deg</td>
</tr>
<tr>
<td>Sharples and Charlesworth [47]</td>
<td>1.5 m above the ridge</td>
<td>$h = 2.2V + 11.9$ (0.5 &lt; $V$ &lt; 6.7) or $h = 9.1V^{0.57}$</td>
</tr>
</tbody>
</table>

Karava et al. 2011
Hypothesis: The convective heat transfer coefficient $h$ depends on solar farm arrangement
Research Question

Can one build a thermal model correlation taking into account solar farm arrangement strategies?
Can we modify the cooling capacity of solar farms through changes in module arrangements?

- Changes in row spacing
- Changes in module heights
- Changes in module tilt angles
- Combination of module heights …
- Changes in farm row configurations & addition of flow deflectors
- Addition of vortex generators

Use a combination of wind tunnel and field experiments & numerical simulations to explore the parameter space.

(a) **Large-Eddy Simulations** MPMICE (Material Point Method, Implicit, Continuous fluid, Eulerian) method: cell-centered, finite-volume, multi-material (Kashiwa & Rauenzahn, LANL 1994, Sulsky et al. 1994 & 1995, Guilkey et al. 2007)

Turbulence Inflow:
(Grid Turbulence generator, Hayati et al 2017.)
Instantaneous temperature fields
Analysis of the interaction between the flow field and the thermal field
(b) **Wind tunnel Measurements**

\[
\alpha = \{15^\circ, 30^\circ, 45^\circ, -30^\circ\}
\]

\[
U_\infty = 1 \text{ m/s}; 3.9 \text{ m/s}
\]

\[
TI = 11\%; 16\%; 18\%
\]
(b) **Wind tunnel Measurements**

Glick et al. 2020, Solar Energy
(c) **Field Measurements**
U.S. Army Dugway Proving Grounds  Solar Farm

Array of turbulence measuring sensors & solar panel thermal characteristics
New Panel Convection Modelling: Geometry-dependent Model

**Present goal:** Define convective cooling of *any solar farm* based on *multiple parameters*.

![Graph showing relationship between $Re^{1/5} Pr^{1/12}$ and $Nu$]
New Panel Convection Modelling: Geometry-dependent Model

\[ Nu = \frac{hL_p}{k} = \text{Convection coefficient * Solar Panel Length} / \text{Thermal conductivity of air} = \text{cooling capabilities along the solar panel surface} \]

\[ h = \frac{Q}{A_p(T_p - T_\infty)} \quad \left[ \frac{W}{m^2K} \right] \]

\[ Nu = \frac{\frac{U^2}{L^2}}{\frac{1}{Re^{1/5} Pr^{1/12}}} \]
New Panel Convection Modelling: Geometry-dependent Model

\[ R_e = \frac{U_\infty L_{sc}}{\nu_k} = \frac{\text{inertial forces}}{\text{viscous forces}} = \frac{(\text{Wind velocity}) \times [\text{Lacunarity (3D geometry scale)]}}{\text{viscosity of the air}} \]
New Panel Convection Modelling: Geometry-dependent Model

\[ Re = \frac{U_\infty L_{nc}}{\nu_k} \]

inertial forces
viscous forces

\[ = \frac{\text{WIND velocity}}{\nu_k} \times \text{Lacunarity (3D geometry scale)} \times \text{viscosity of the air} \]

Most heterogeneous/diverse arrangement

Representing 9 different variations in terms of 3D space
New Panel Convection Modelling: Geometry-dependent Model

\[ Pr = \frac{\langle u'w' \rangle (\frac{\partial \bar{u}}{\partial x})^{-1}}{\langle \bar{w}' \bar{\phi}' \rangle (\frac{\partial \bar{v}}{\partial y})^{-1}} = \frac{\text{momentum diffusion}}{\text{thermal diffusion}} = \text{how well mixing works to diffuse the heat} \]
New Panel Convection Modelling: Geometry-dependent Model

\[ N_u = c(Re^a Pr^b) + N_o \] (similar to: \( y = mx + b \))
Scaling for the convective heat transfer in solar farms & gains in harvested power

Configurations leading to power gains!
Conclusions

• Simple changes in solar module arrangements in solar farms have the potential to lead to important gains in power efficiency.

• An improve model taking into account such variations.

• The same way that the wind energy industry realized that local meteorology and turbulence matter, the solar PV industry could take into consideration not only the effects of module arrangements, but also the local meteorology (i.e. beyond incident solar radiation) when installing solar farms.

• We just started scratching the surface of the potential improvements to be gained when considering fluid mechanics and turbulence…