

**THERMAL ANALYSIS AND COOLING OF SOLAR PHOTOVOLTAIC SYSTEMS
TO CURB THEIR TEMPERATURE RISE-DRIVEN PERFORMANCE LOSS**

SHUBHAM KUMAR



**DEPARTMENT OF MECHANICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
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by

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Submitted

in fulfilment of the requirements of the degree of Doctor of Philosophy

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Dedicated to my parents, my wife, and
my beloved son, Darsh.

CERTIFICATE

This is to certify that the thesis entitled, “**Thermal analysis of solar Photovoltaic systems to curb their temperature rise-driven performance loss**”, being submitted by **Mr. Shubham Kumar** to the Indian Institute of Technology Delhi, India, for award of degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him. He has worked under my guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to my knowledge has reached the requisite standard.

The results contained in the thesis have not been submitted, in part or full, to any other university or institute for the award of any degree or diploma.

Place: New Delhi

Dr. P.M.V. Subbarao

Professor

Department of Mechanical Engineering

Indian Institute of Technology Delhi

New Delhi-110016 (INDIA)

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(Mr. Shubham Kumar)

ABSTRACT

The share of solar photovoltaics (PV) in total electricity generation capacity has increased steadily over the years, both in India and globally. However, several practical challenges continue to limit their real field performance. Elevated operating temperature is a key concern, as it reduces the PV efficiency and enhances the degradation rate, thereby diminishing the returns from a PV system. Temperature non-uniformities within the PV system further worsen these adverse effects. Thus, effective and viable thermal management of solar PV systems is essential for ensuring their sustained and dependable operation. Besides, accurate prediction of real field temperature and corresponding output is also necessary for smooth grid management.

The research work conducted under this thesis aims to predict and analyse the thermal behaviour of PV systems, and to design and develop effective cooling strategies for their thermal management. Firstly, a network-based transient thermal model is developed, which predicts the experimental cell temperature with a mean error of 0.88°C (7.8%) only. Furthermore, a novel hybrid function for PV efficiency is proposed which predicts efficiency and power with respective errors of 1.62% and 1.32% on a sunny and with 1.25% and 1.04% on a cloudy day – showing higher accuracy over pre-existing and popular PV efficiency functions. The thermal model compares the contributions of free convection, forced convection and radiation heat transfer over a wide range of wind speeds ($V = 0.5\text{--}5\text{ m/s}$), showing that free convection is relevant for $V \leq 1\text{ m/s}$, while radiation contributes significantly to the total heat transfer across all wind speeds. The model further predicts 8.4% loss in annual output of a PV array in Delhi's climate due to operating temperature elevating above ambient.

Subsequently, considering the inferences from the network-based thermal model, a novel multi-cell computational heat transfer (CHT) model is developed for comprehensive analysis of the thermal profile and convective characteristics of a free-standing PV module. The analysis is performed in a wide range of field-representative wind conditions ($V = 0.5\text{-}5\text{ m/s}$) and wind directions ($\alpha = 0^\circ\text{-}180^\circ$) – an area largely underexplored in the previous studies. An innovative test rig is fabricated for direct measurement of cell temperature, obtaining the thermal profile and efficiency of PV module, and validation of the CHT model. The experimental cell-to-back temperature difference, normalised at one sun, ranges from 3.6°C to 4.4°C . These results validate the findings from the multi-cell model and demonstrate its superiority over pre-existing single-cell CHT models. Wind direction has a marginal effect of only up to 1.1°C on the average cell temperature. However, temperature profile patterns show a correlation coefficient above 0.83 for a specific wind direction across varying wind speeds, indicating those are largely dependent on the wind direction and are predictable for a known wind rose pattern. The flow field and backside convective behaviour are strongly influenced by the wind direction. Flow separation and vortex formation on one side can increase convection by up to 1.8 times compared to the other side. The detailed flow analysis offers valuable insights for improving the thermal behaviour of PV systems and guiding the design of cooling methods.

Fins-based cooling emerges as a promising passive strategy for PV systems in the literature due to reliable performance across diverse climates and negligible maintenance requirements. Rectangular segmented fins are proposed in this work for enhanced flow mixing and higher cooling potential, while also saving in material usage. The effects of the relevant fin parameters on the cell temperature, thermal uniformity and economic viability are largely underexplored in

the literature and constitute a major objective of this work. The heat sink performance evaluations are conducted using a CHT model, which is further validated against experimental data from a second test rig. Building on the insights from the preceding thermal analysis, heat sink performance is investigated over a wide range of wind directions and tilt angles using detailed flow and turbulence analysis.

For a PV system tilted at 25° , all fin configurations consistently provide the least cooling under $\alpha = 0^\circ$ - 45° and maximum cooling under $\alpha = 90^\circ$ - 135° . The same is observed in the experimental studies. The inclusion of a base plate is found to be critical for high degree of cooling as well as improved temperature uniformity. Narrower fins with adequate segmentation gap maximise the degree of cooling and material savings, with 4.5 wide fins at 2 cm segmentation gap identified as the optimal configuration. A spacing of 2 cm between fin rows yields the maximum benefit-to-cost ratio, offering 6.6°C cooling and 3% efficiency improvement at $\alpha = 135^\circ$. Longer fins are found to be more effective than higher number of fin rows at $\alpha = 0^\circ$, 45° and 90° . For 8 cm long fins, $\alpha = 90^\circ$ observes maximum cooling of 6.5°C . Staggered fin arrangement provides up to 20% higher cooling than linear arrangement at $\alpha = 45^\circ$ and 90° and almost similar cooling in other wind directions. Overall, the optimised configuration improves the benefit-to-cost ratio by more than 25% compared to conventional rectangular fin configuration reported in the literature. Lowering the tilt angle increases the degree of PV cooling under $\alpha = 0^\circ$ and 45° by up to 2 times, indicating viability of fins-based cooling solutions in all wind directions for locations close to the equator. The overall analysis offers crucial design improvements to enhance fin heat sink performance in the thermal management of PV systems and informs the strengths and limitations of their application for installations at specific latitudes and prevailing wind rose patterns.

सार

सौर फोटोवोल्टाइक (PV) की कुल विद्युत उत्पादन क्षमता में हिस्सेदारी भारत तथा विश्व स्तर पर वर्षों से लगातार बढ़ रही है। हालांकि, कई व्यावहारिक चुनौतियाँ अभी भी इनके वास्तविक प्रदर्शन को सीमित करती हैं। उच्च संचालन तापमान एक प्रमुख समस्या है, क्योंकि यह PV की दक्षता को कम करता है तथा इसके क्षरण की दर को बढ़ाता है, जिससे PV प्रणाली से प्राप्त होने वाला लाभ घट जाता है। PV प्रणाली के भीतर तापमान की असमानताएँ इन प्रतिकूल प्रभावों को और अधिक बढ़ा देती हैं। इसलिए, सौर PV प्रणालियों का प्रभावी एवं व्यवहार्य तापीय प्रबंधन उनके दीर्घकालिक और विश्वसनीय संचालन को सुनिश्चित करने के लिए अत्यंत आवश्यक है। इसके अतिरिक्त, सुचारु ग्रिड प्रबंधन के लिए वास्तविक क्षेत्रीय तापमान तथा उससे संबंधित विद्युत उत्पादन का सटीक पूर्वानुमान भी आवश्यक है।

इस शोध प्रबंध के अंतर्गत किया गया शोध कार्य PV प्रणालियों के तापीय व्यवहार का पूर्वानुमान एवं विश्लेषण करने तथा उनके तापीय प्रबंधन के लिए प्रभावी शीतलन रणनीतियों के डिजाइन और विकास पर केंद्रित है। सर्वप्रथम, एक नेटवर्क-आधारित क्षणिक तापीय मॉडल विकसित किया गया, जो प्रायोगिक सेल तापमान का पूर्वानुमान केवल 0.88°C (7.8%) की औसत त्रुटि के साथ करता है। इसके अतिरिक्त, PV दक्षता के लिए एक नवीन हाइब्रिड फलन प्रस्तावित किया गया, जो धूप वाले दिन दक्षता और शक्ति का पूर्वानुमान क्रमशः 1.62% और 1.32% की त्रुटि के साथ तथा बादल वाले दिन 1.25% और 1.04% की त्रुटि के साथ करता है — जो पूर्व-प्रचलित और लोकप्रिय PV दक्षता फलनों की तुलना में अधिक सटीकता दर्शाता है। तापीय मॉडल $0.5\text{--}5\text{ m/s}$ की विस्तृत पवन वेग सीमा पर मुक्त संवहन, बलपूर्वक संवहन तथा विकिरण ऊष्मा स्थानांतरण के योगदानों की तुलना करता है, जिससे यह स्पष्ट होता है कि $V \leq 1\text{ m/s}$ पर मुक्त संवहन महत्वपूर्ण रहता है, जबकि सभी पवन वेगों पर कुल ऊष्मा स्थानांतरण में विकिरण का योगदान उल्लेखनीय बना रहता है। यह मॉडल आगे यह भी दर्शाता है कि दिल्ली की जलवायु में परिवेश तापमान की तुलना में अधिक संचालन तापमान के कारण PV ऐरे के वार्षिक विद्युत उत्पादन में 8.4% की हानि होती है।

इसके पश्चात, नेटवर्क-आधारित तापीय मॉडल से प्राप्त निष्कर्षों को ध्यान में रखते हुए, एक नवीन बहु-सेल संगणकीय ऊष्मा स्थानांतरण (Computational Heat Transfer, CHT) मॉडल विकसित किया गया, ताकि स्वतंत्र रूप से स्थापित PV मॉड्यूल के तापीय प्रोफ़ाइल तथा संवहन विशेषताओं का व्यापक विश्लेषण किया जा सके। यह विश्लेषण वास्तविक क्षेत्रीय परिस्थितियों का प्रतिनिधित्व करने वाली विस्तृत पवन दशाओं ($V = 0.5\text{--}5\text{ m/s}$) तथा पवन दिशाओं ($\alpha = 0^\circ\text{--}180^\circ$) में किया गया — जो पूर्ववर्ती अध्ययनों में काफी हद तक अन्वेषित नहीं किया गया क्षेत्र है। सेल तापमान के प्रत्यक्ष मापन, PV मॉड्यूल के तापीय प्रोफ़ाइल एवं दक्षता प्राप्त करने तथा CHT मॉडल के प्रमाणीकरण के लिए एक अभिनव परीक्षण संयंत्र (test rig) तैयार किया गया। एक सन (one sun) पर सामान्यीकृत प्रायोगिक सेल-से-बैक तापमान अंतर 3.6°C से 4.4°C के बीच पाया गया। ये परिणाम बहु-सेल मॉडल के निष्कर्षों की पुष्टि करते हैं तथा पूर्व-प्रचलित एकल-सेल CHT मॉडलों की तुलना में इसकी श्रेष्ठता प्रदर्शित करते हैं। पवन दिशा का औसत सेल तापमान पर केवल 1.1°C तक का सीमित प्रभाव पाया गया। हालांकि, तापमान प्रोफ़ाइल के प्रतिरूप विभिन्न पवन वेगों पर किसी विशिष्ट पवन दिशा के लिए 0.83 से अधिक सहसंबंध गुणांक प्रदर्शित करते हैं, जिससे संकेत मिलता है कि वे मुख्यतः पवन दिशा पर निर्भर होते हैं तथा ज्ञात पवन वितरण प्रतिरूप (wind rose pattern) के लिए पूर्वानुमेय हैं। प्रवाह क्षेत्र तथा पीछे की ओर का संवहन व्यवहार पवन दिशा से अत्यधिक प्रभावित होता है। एक ओर प्रवाह पृथक्करण तथा भंवर निर्माण दूसरी ओर की तुलना में संवहन को 1.8 गुना तक बढ़ा सकता है। यह विस्तृत प्रवाह विश्लेषण PV प्रणालियों के तापीय व्यवहार में सुधार तथा शीतलन विधियों के डिजाइन के लिए महत्वपूर्ण अंतर्दृष्टि प्रदान करता है।

साहित्य में फिन-आधारित शीतलन PV प्रणालियों के लिए एक आशाजनक निष्क्रिय रणनीति के रूप में उभरता है, क्योंकि यह विभिन्न जलवायु परिस्थितियों में विश्वसनीय प्रदर्शन प्रदान करता है तथा इसकी रखरखाव आवश्यकताएँ नगण्य होती हैं। इस शोध कार्य में बेहतर प्रवाह मिश्रण एवं अधिक शीतलन क्षमता प्राप्त करने के साथ-साथ सामग्री उपयोग में बचत हेतु आयताकार खंडित फिन (rectangular segmented fins) प्रस्तावित किए गए हैं। साहित्य में संबंधित फिन मानकों के सेल तापमान, तापीय समानता तथा आर्थिक व्यवहार्यता पर प्रभावों का व्यापक अध्ययन अभी तक नहीं किया गया है, और यही इस कार्य के प्रमुख उद्देश्यों में से एक है। हीट सिंक के प्रदर्शन का

मूल्यांकन एक CHT मॉडल का उपयोग करके किया गया, जिसे आगे दूसरे परीक्षण संयंत्र (test rig) से प्राप्त प्रायोगिक आंकड़ों द्वारा सत्यापित किया गया। पूर्ववर्ती तापीय विश्लेषण से प्राप्त अंतर्दृष्टियों के आधार पर, हीट सिंक के प्रदर्शन का अध्ययन विस्तृत प्रवाह एवं अशांति (turbulence) विश्लेषण के माध्यम से विभिन्न पवन दिशाओं तथा झुकाव कोणों की विस्तृत सीमा में किया गया।

25° पर झुकी हुई PV प्रणाली के लिए, सभी फिन विन्यास $\alpha = 0^\circ - 45^\circ$ पर लगातार न्यूनतम शीतलन तथा $\alpha = 90^\circ - 135^\circ$ पर अधिकतम शीतलन प्रदान करते हैं। यही प्रवृत्ति प्रायोगिक अध्ययनों में भी देखी गई। उच्च स्तर के शीतलन तथा बेहतर तापीय समानता के लिए आधार प्लेट (base plate) का समावेशन अत्यंत महत्वपूर्ण पाया गया। पर्याप्त खंडन अंतराल (segmentation gap) वाले संकरे फिन शीतलन स्तर एवं सामग्री बचत को अधिकतम करते हैं, जिसमें 2 सेमी खंडन अंतराल पर 4.5 सेमी चौड़े फिन को सर्वोत्तम विन्यास के रूप में पहचाना गया। फिन पंक्तियों के बीच 2 सेमी की दूरी अधिकतम लाभ-से-लागत अनुपात प्रदान करती है, जिससे $\alpha = 135^\circ$ पर 6.6°C तक शीतलन तथा 3% दक्षता वृद्धि प्राप्त होती है। $\alpha = 0^\circ, 45^\circ$ और 90° पर अधिक संख्या में फिन पंक्तियों की तुलना में लंबे फिन अधिक प्रभावी पाए गए। 8 सेमी लंबे फिन के लिए, $\alpha = 90^\circ$ पर 6.5°C का अधिकतम शीतलन प्राप्त हुआ। क्रमविन्यस्त (staggered) फिन व्यवस्था $\alpha = 45^\circ$ और 90° पर रैखिक व्यवस्था की तुलना में 20% तक अधिक शीतलन प्रदान करती है तथा अन्य पवन दिशाओं में लगभग समान शीतलन देती है। समग्र रूप से, अनुकूलित विन्यास साहित्य में वर्णित पारंपरिक आयताकार फिन विन्यास की तुलना में लाभ-से-लागत अनुपात में 25% से अधिक सुधार करता है। झुकाव कोण को कम करने से $\alpha = 0^\circ$ और 45° पर PV शीतलन की मात्रा में 2 गुना तक वृद्धि होती है, जो भूमध्य रेखा के निकट स्थित स्थानों के लिए सभी पवन दिशाओं में फिन-आधारित शीतलन समाधानों की व्यवहार्यता को दर्शाता है। यह समग्र विश्लेषण PV प्रणालियों के तापीय प्रबंधन में फिन हीट सिंक के प्रदर्शन को बेहतर बनाने हेतु महत्वपूर्ण डिजाइन सुधार प्रस्तुत करता है तथा विशिष्ट अक्षांशों और प्रचलित पवन वितरण प्रतिरूपों (wind rose patterns) वाले स्थलों पर इनके अनुप्रयोग की शक्तियों एवं सीमाओं की जानकारी प्रदान करता है।

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NOMENCLATURE			
A	Area	T_o	Ambient temperature
a	Absorptance of PV system	T_b	Backside temperature
a_g	Absorption coefficient of ground	T_f	Frontside temperature
c	Specific heat capacity	T_{fins}	Temperature of fins
d	Segmentation gap between fins	T_g	Temperature of ground
$\bar{d}_i$	Thickness of layer/domain	T_{pv}	Temperature of PV module
E	Energy of photon	T_s	Sky temperature
E_g	Band gap	t_b	Base thickness
f	Packing density of PV module	t_f	Fin thickness
FF	Fill factor	ΔT	Degree of overheating
G	Solar irradiance	U	Overall heat transfer coefficient
h	Convection coefficient	$\bar{u}_i$	Mean velocity component
I	Electric current	u'_i	Fluctuating velocity component
I_{mpp}	Current at maximum power point	$\mathcal{V}$	Electric voltage
I_{sc}	Short circuit current	$\mathcal{V}_{mpp}$	Voltage at maximum power point
k	Turbulent kinetic energy	$\mathcal{V}_{oc}$	Open circuit voltage
k'	Thermal conductivity	V	Wind speed
k_T	Sky clearness index	V'	Volume
k_D	Diffusion constant	W	Width of PV module
L	Length of PV module	y^+	Dimensionless distance

l	Fin length		
m	Mass	α	Wind angle/direction
N	Number of fins	β	Temperature coefficient
P	Pressure	γ	Irradiance coefficient
P_{elec}	Electric power	ϵ	Emissivity
P_{mpp}	Power at maximum power point	μ	Dynamic viscosity
$\dot{q}$	Rate of heat transfer	ω	Specific dissipation rate
Q^{gen}	Volumetric heat generation rate	ρ	Density
Q''	Heat flux	η	PV efficiency
R_T	Thermal resistance	θ	Tilt angle of PV system
s	Fin row spacing	τ	Transmittance of PV system
t	Time	τ_c	Time constant
T	Cell temperature	ν	Kinematic viscosity
Abbreviations			
CFD	Computational fluid dynamics	PV	Photovoltaics
CHT	Computational heat transfer	RANS	Reynolds averaged Navier Stokes
c-Si	Crystalline silicon	SHJ	Silicon hetero junction
DTNU	Degree of temp non-uniformity	STC	Standard testing conditions
EVA	Ethyl vinyl acetate	SST	Shear stress transport
LCOE	Levelized cost of electricity	TFT	Thin film temperature
RTD	Resistance temperature detector	TKE	Turbulent kinetic energy