MODELLING AND ANALYSIS OF SOLAR COMPOUND PARABOLIC COLLECTOR WITH A TUBULAR RECEIVER FOR SOLAR COOLING APPLICATIONS

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by

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Certificate

This is to certify that the thesis entitled "**Modelling and Analysis of Solar Compound Parabolic Collector with a Tubular Receiver for Solar Cooling Applications** " being submitted by **Mrs. Aditi Garg** to the **Indian Institute of Technology Delhi**, New Delhi, India, for the award of the degree of **Doctor of Philosophy** is a record of original bonafide research work carried out by her under our guidance and supervision, and the results contained in it have not been submitted in part or full to any other university or institute for award of any degree or diploma.

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Abstract

Solar energy, being clean and abundantly available, is well-suited to meet space cooling demands. Among the various solar thermal collector options, Compound Parabolic Collectors (CPC) have gained particular attention due to their ability to collect diffuse solar radiation, concentrate solar radiation, operate without tracking, and achieve higher temperatures than flat plate collectors. These features make CPC suitable for applications such as solar cooling using vapour absorption systems.

This research includes a detailed thermal and optical analysis of the CPC solar collector and a techno-economic analysis of the CPC integrated with a single-effect vapour absorption system. The heat losses are a critical aspect of the thermal performance of a solar collector and account for a considerable portion of the heat energy absorbed by the collector. Numerical models of CPC with a non-evacuated tubular receiver are developed in both 2D and 3D to examine the influence of various operating parameters (receiver temperature, inlet fluid velocity and inlet fluid temperature), environmental parameters (ambient temperature, wind heat transfer coefficient) and design parameters (truncation ratio, tilt angles, insulation and aperture cover thickness, surface emissivities) on the convective and radiative heat losses, fluid temperature rise, thermal efficiency and Nusselt number, further leading to development of Nusselt number correlations.

The operating and environmental parameters, as well as receiver emissivity, are found to significantly impact thermal performance, with the effect of inlet fluid velocity majorly on the rise in fluid temperature. The effect of tilt angles is found to be insignificant on heat losses. The truncation ratio affects the thermal performance by 9% when the height of the collector is reduced by 60%. The truncation also helps save reflector material by 43% in weight.

A comparative study analysing the effect of pure convection versus combined convection and surface radiation showed that total heat losses and Nusselt number increased by 7.7% and 41.2% for receiver emissivities of 0.05 and 0.9, respectively, compared to the pure convection case. This highlights the significant role of radiative effects in heat transfer, which have often been neglected in previous studies.

A notable difference is observed between the Nusselt number obtained from 2D and 3D numerical models, primarily due to enhanced fluid mixing and heat transfer in the 3D model resulting from vortex formation. The two Nusselt number correlations developed are compared with other correlations available from the literature, and the discrepancies are attributed to

simplified modelling assumptions and the omission of radiative heat losses, all of which influence both the magnitude and trend of the Nusselt number.

A detailed ray-tracing optical model of the CPC is developed to investigate the effects of circumsolar ratio, sunshape, and surface errors on its optical performance. The results indicate that optical errors lead to a maximum variation of 1% in absorbed heat, suggesting that the CPC geometry is largely unaffected by minor optical imperfections. Further, the heat flux obtained from the optical model is integrated with the 3D numerical model of CPC for complete analysis.

A 3D model of an evacuated tubular receiver CPC is developed and compared with the non-evacuated receiver CPC. The analysis reveals a significant 56% reduction in total heat loss, primarily due to the elimination of convective losses. This results in an increase in thermal efficiency from 59% to 76% and a rise in fluid outlet temperature from 2.88 K to 3.76 K. Thermal efficiency equations are derived for both models and used in the solar absorption cooling model.

A CPC-based solar absorption cooling system model is developed in TRNSYS to study the thermal, economic, and environmental performance of the system. Analyses are performed to assess the effect of parameters like collector area, collector slope, storage tank specific volume ratio (STSVR) and CPC design (evacuated vs. non-evacuated) on solar fraction (SF), payback period (PBP), levelized cost of cooling (LCOC) and carbon dioxide emissions (CDE).

The collector area significantly affected the thermal, economic and environmental performance of solar absorption cooling systems, making it a key design parameter. In contrast, the collector slope primarily influenced thermal performance, with negligible effects on economic and environmental metrics. The STSVR directly impacted the economic and environmental outcomes by increasing the PBP, LCOC and CDE. However, thermal performance, measured in terms of the solar fraction, decreased with increasing STSVR for a fixed collector area. No substantial improvement is observed beyond an STSVR of 0.02 m^3/m^2, indicating limited thermal advantage at higher storage volumes.

The comparison of the performances of the non-evacuated and evacuated receiver CPC indicated an improvement in the solar fraction by 14%, a reduction in both the discounted payback period by 5.25 years, and CO_2 emissions by 4.3 tonnes annually for New Delhi.

A climatic comparison across global cities showed that locations with high solar potential (e.g., Cairo, Phoenix) achieved favorable economics, with LCOC less than 20 INR/kWh and discounted payback periods under 13 years. The medium solar potential cities (Rome, New

Delhi) exhibiting different climatic conditions and cooling loads lead to comparable differences in their LCOC values of 25.73 INR/kWh and 33.95 INR/kWh respectively with a similar PBP of 17.3 years. In contrast, low solar potential cities (e.g., Kuala Lumpur, Taipei) resulted in LCOC above 37 INR/kWh and payback periods exceeding 24 years. This indicates that these locations are economically unviable and will require alternative strategies to improve economic viability.

The analysis also resulted in the proposal of two new metrics, the solar cooling cost metric (SCCM) and carbon dioxide emission factor for solar cooling (CDEFSC), aimed to assess the cost and environment-related aspects of solar cooling systems across different locations.

Overall, this work contributes to an enhanced understanding of the performance of CPC and its application in solar absorption cooling systems.

सार

सौर ऊर्जा स्वच्छ और प्रचुर मात्रा में उपलब्ध होने के कारण स्थान शीतलन आवश्यकताओं को पूरा करने के लिए उपयुक्त है। विभिन्न सौर तापीय कलेक्टर विकल्पों में, यौगिक परावैधिक कलेक्टर (Compound Parabolic Collector - CPC) ने विशेष ध्यान आकर्षित किया है क्योंकि ये विसरित सौर विकिरण को एकत्र करने, सौर विकिरण को संकेंद्रित करने, ट्रैकिंग के बिना कार्य करने और फ्लैट प्लेट कलेक्टरों की तुलना में अधिक तापमान प्राप्त करने में सक्षम हैं। ये विशेषताएँ CPC को वाष्प अवशोषण प्रणालियों द्वारा सौर शीतलन जैसे अनुप्रयोगों के लिए उपयुक्त बनाती हैं।

इस शोध में CPC सौर कलेक्टर का विस्तृत तापीय और प्रकाशीय विश्लेषण तथा एकल-प्रभाव वाष्प अवशोषण प्रणाली के साथ एकीकृत CPC का तकनीकी-आर्थिक विश्लेषण शामिल है। सौर कलेक्टर की तापीय दक्षता में तापीय हानियाँ महत्वपूर्ण भूमिका निभाती हैं और यह कलेक्टर द्वारा अवशोषित ऊष्मा ऊर्जा का एक बड़ा हिस्सा प्रभावित करती हैं। गैर-रिक्तन (non-evacuated) ट्यूबुलर रिसीवर वाले CPC के 2D और 3D संख्यात्मक मॉडल विकसित किए गए हैं, जिनमें विभिन्न परिचालन पैरामीटर (जैसे रिसीवर तापमान, तरल वेग, तरल तापमान), पर्यावरणीय पैरामीटर (वातावरण तापमान, पवन ऊष्मा स्थानांतरण गुणांक), तथा डिजाइन पैरामीटर (ट्रन्केशन अनुपात, झुकाव कोण, इंसुलेशन व एपर्चर कवर की मोटाई, सतह उत्सर्जकता) के प्रभावों का अध्ययन किया गया है। इनका प्रभाव संवाहक व विकिरणीय ऊष्मा हानियों, द्रव तापमान वृद्धि, तापीय दक्षता और नुस्सेल्ट संख्या पर देखा गया, जिससे नुस्सेल्ट संख्या के सहसंबंध विकसित किए गए।

यह पाया गया कि परिचालन व पर्यावरणीय पैरामीटर और रिसीवर की उत्सर्जकता तापीय प्रदर्शन को उल्लेखनीय रूप से प्रभावित करते हैं। तरल वेग का प्रभाव मुख्य रूप से द्रव तापमान में वृद्धि पर पड़ता है। झुकाव कोण का ऊष्मा हानियों पर कोई महत्वपूर्ण प्रभाव नहीं पाया गया। ट्रन्केशन अनुपात में 60% ऊँचाई घटाने पर तापीय प्रदर्शन में लगभग 9% की गिरावट आती है, जबकि परावर्तक सामग्री के भार में 43% की बचत होती है।

शुद्ध संवहन बनाम संयुक्त संवहन और सतही विकिरण के प्रभाव की तुलनात्मक अध्ययन से पता चला कि रिसीवर की उत्सर्जकता 0.05 से 0.9 करने पर कुल ऊष्मा हानि में 7.7% और नुस्सेल्ट संख्या में 41.2% की वृद्धि होती है, जिससे विकिरणीय प्रभाव की महत्ता स्पष्ट होती है, जिसे पूर्ववर्ती शोधों में अक्सर अनदेखा किया गया है।

2D और 3D मॉडल से प्राप्त नुस्सेल्ट संख्या में महत्वपूर्ण अंतर देखा गया, जो मुख्यतः 3D मॉडल में बेहतर द्रव मिश्रण और भंवर (vortex) निर्माण के कारण हुआ। विकसित किए गए दो नुस्सेल्ट संख्या सहसंबंधों की तुलना साहित्य से प्राप्त सहसंबंधों से की गई, जहाँ अंतर के कारणों को सरलीकृत मॉडलिंग मान्यताओं और विकिरणीय हानियों की अनदेखी बताया गया।

CPC का एक विस्तृत रे-ट्रेसिंग ऑप्टिकल मॉडल विकसित किया गया जिसमें circumsolar अनुपात, सूरज का आकार, और सतह त्रुटियों के ऑप्टिकल प्रदर्शन पर प्रभावों का अध्ययन किया गया। परिणामों से पता चला कि सतह की त्रुटियाँ अवशोषित ऊष्मा में अधिकतम 1% परिवर्तन का कारण बनती

हैं, जो दर्शाता है कि CPC की ज्यामिति छोटी ऑप्टिकल त्रुटियों से बहुत प्रभावित नहीं होती। इसके अलावा, ऑप्टिकल मॉडल से प्राप्त ऊष्मा फ्लक्स को 3D संख्यात्मक मॉडल के साथ जोड़ा गया।

रिक्तन ट्यूब रिसीवर वाले CPC का एक 3D मॉडल भी विकसित किया गया और इसे गैर-रिक्तन रिसीवर CPC से तुलना की गई। विश्लेषण से यह ज्ञात हुआ कि कुल ऊष्मा हानि में 56% की कमी आती है, जो मुख्यतः संवाहक हानियों की समाप्ति से होती है। इसके परिणामस्वरूप तापीय दक्षता 59% से 76% तक बढ़ जाती है और आउटलेट तापमान में 2.88 K से 3.76 K की वृद्धि होती है। दोनों मॉडलों के लिए तापीय दक्षता समीकरण बनाए गए जिन्हें सौर अवशोषण शीतलन मॉडल में उपयोग किया गया।

CPC आधारित सौर वाष्प अवशोषण शीतलन प्रणाली का मॉडल TRNSYS में विकसित किया गया, जिसमें तापीय, आर्थिक और पर्यावरणीय प्रदर्शन का अध्ययन किया गया। कलेक्टर क्षेत्रफल, कलेक्टर का झुकाव, स्टोरेज टैंक विशिष्ट आयतन अनुपात (STSVR) और CPC डिज़ाइन (रिक्तन बनाम गैर-रिक्तन) जैसे पैरामीटरों का सौर अंश (SF), पेबैक अवधि (PBP), स्तरीकृत शीतलन लागत (LCOC), और कार्बन डाइऑक्साइड उत्सर्जन (CDE) पर प्रभाव का आकलन किया गया।

कलेक्टर क्षेत्र का तापीय, आर्थिक और पर्यावरणीय प्रदर्शन पर अत्यधिक प्रभाव पाया गया, जिससे यह एक प्रमुख डिजाइन पैरामीटर बन गया। इसके विपरीत, कलेक्टर के झुकाव का प्रभाव मुख्यतः तापीय प्रदर्शन पर था। STSVR ने आर्थिक व पर्यावरणीय प्रदर्शन पर सीधा प्रभाव डाला, जिससे PBP, LCOC, और CDE में वृद्धि हुई। हालांकि, STSVR बढ़ने से सौर अंश घटा। 0.02 m^3/m^2 से अधिक STSVR पर कोई उल्लेखनीय सुधार नहीं पाया गया।

गैर-रिक्तन और रिक्तन CPC की तुलना में सौर अंश में 14% की वृद्धि, छूटयुक्त पेबैक अवधि में 5.25 वर्ष की कमी, और CO_2 उत्सर्जन में प्रति वर्ष 4.3 टन की कमी देखी गई (नई दिल्ली के लिए)।

विश्व के विभिन्न शहरों के जलवायु तुलनात्मक अध्ययन में पाया गया कि उच्च सौर क्षमता वाले शहरों (जैसे काहिरा, फीनिक्स) में LCOC 20 INR/kWh से कम और पेबैक अवधि 13 वर्षों से कम रही। मध्यम सौर क्षमता वाले शहरों (जैसे रोम, नई दिल्ली) में अलग-अलग जलवायु परिस्थितियाँ और शीतलन भार होने के कारण क्रमशः 25.73 और 33.95 INR/kWh की LCOC और समान पेबैक अवधि (17.3 वर्ष) पाई गई। जबकि निम्न सौर क्षमता वाले शहरों (जैसे कुआलालंपुर, ताइपेई) में LCOC 37 INR/kWh से अधिक और पेबैक अवधि 24 वर्षों से अधिक रही, जो इन स्थानों को आर्थिक रूप से अनुपयुक्त बनाती है।

इस अध्ययन के अंतर्गत दो नए संकेतकों का प्रस्ताव किया गया: सौर शीतलन लागत संकेतक (SCCM) और सौर शीतलन हेतु कार्बन डाइऑक्साइड उत्सर्जन गुणांक (CDEFSC), जो विभिन्न स्थानों में सौर शीतलन प्रणालियों की लागत और पर्यावरणीय प्रभाव का मूल्यांकन करते हैं।

कुल मिलाकर, यह शोध CPC के प्रदर्शन और उसके सौर अवशोषण शीतलन अनुप्रयोगों की बेहतर समझ में महत्वपूर्ण योगदान देता है।

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Nomenclature

Roman Symbols	Description	Units
A_{ap}	aperture surface area	m^2
A_r	receiver surface area	m^2
A_{sc}	aperture area of solar collector panel	m^2
A_x	transverse aspect ratio	-
A_z	longitudinal aspect ratio	-
C_p	specific heat capacity	$J\ kg^{-1}.K^{-1}$
$C_{1\varepsilon}, C_{2\varepsilon}, C_\mu$	turbulence model constants	-
D	diameter of receiver	m
E_{aux}	auxiliary heat provided by boiler	W
E_u	useful energy gain	W
G_b	generation of turbulence kinetic energy due to buoyancy	$kg\ m^{-1}\ s^{-3}$
G_k	generation of turbulence kinetic energy due to mean velocity gradients	$kg\ m^{-1}\ s^{-3}$
Gr_d	Grashof number based on receiver diameter	-
Gr_L	Grashof number based on characteristic length	-
g	gravitational acceleration	$m\ s^{-2}$
h	heat loss coefficient	$W\ m^{-2}\ K^{-1}$
H	height of CPC	m
H_{tr}	truncated height	m
h_w	wind heat transfer coefficient	$W\ m^{-2}\ K^{-1}$
k	turbulent kinetic energy	$m^2\ s^{-2}$
L	length of collector	m
m	mass flow rate	$kg\ s^{-1}$
Nu_H	Nusselt number based on height of CPC	-
Nu_L	Nusselt number based on characteristic length	-
P	pressure	Pa
Pr	Prandtl number	-
Q_a	heat absorbed by receiver	W

Q_{ABS}	chiller capacity	kW
Q_{ap}	solar radiations received on aperture cover	W
Q_C	convective heat loss from receiver	W
Q_{CT}	capacity of cooling tower	kW
Q_R	radiative heat loss from receiver	W
Q_T	total heat loss from receiver	W
Ra_H	Rayleigh number based on height of CPC	-
Ra_L	Rayleigh number based on characteristic length	-
T	temperature	K
T_a	ambient temperature	K
T_{ap}	aperture cover temperature	K
T_{fi}	inlet fluid temperature	K
T_r	receiver temperature	K
t_{ins}	insulation thickness	m
t_{ap}	aperture cover thickness	m
U	velocity	$m\ s^{-1}$
v_{fi}	inlet fluid velocity	$m\ s^{-1}$
V_{ST}	storage tank volume	m^3
W_{ap}	aperture cover width	m

Greek symbols

α_r	absorptivity of receiver	-
Θ_i	angle of incidence	°
ε_{ap}	aperture cover emissivity	-
ρ	density	$kg\ m^{-3}$
μ	dynamic viscosity	$kg\ m^{-1}\ s^{-1}$
σ_T	effective Prandtl number for T	-
Θ_A	half acceptance angle of CPC	°
ν	kinematic viscosity	m^2/s
Θ	longitudinal tilt angle	°
η_{op}	optical efficiency of the collector	%
ε_r	receiver tube emissivity	-
ε_{ref}	reflector wall emissivity	-

ρ_{ref}	reflectivity of reflector wall	-
σ_{slope}	slope error	mrad
σ_{spec}	specular error	mrad
σ	Stefan-Boltzmann constant	W m^{-2} K^{-4}
ΔT	temperature difference	K
λ	thermal conductivity	W m^{-1} K^{-1}
η_{th}	thermal efficiency of collector	%
β	thermal expansion coefficient	K^{-1}
τ_{ap}	transmissivity of aperture cover	-
φ	transverse tilt angle	°
ε	turbulent dissipation rate of k	m^2 s^{-3}
σ_k	turbulent Prandtl numbers for k	-
σ_ε	turbulent Prandtl numbers for ε	-
μ_t	turbulent viscosity	kg m^{-1} s^{-1}

Abbreviations

C.C	Capital Cost	INR
CDE	Carbon Dioxide Emission	tonnes
CDEFSC	Carbon Dioxide Emission Factor for Solar Cooling	kg CO2/kWh
CFD	Computational Fluid Dynamics	-
COP	Coefficient of Performance	-
CPC	Compound Parabolic Collector	
CR	Concentration Ratio	-
CSR	Circum Solar Ratio	-
CTR	Central Tower Receiver	-
DPBP	Discounted Pay Back Period	years
ETC	Evacuated Tube Collector	-
FIR	Fuel Inflation Rate	-
FPC	Flat Plate Collector	-
IC	Installation Cost	INR
LCOC	Levelized Cost of Cooling	INR/kWh
LFR	Linear Fresnel Reflector	-

M.C	Maintenance Cost	INR
O.C	Operating Cost	INR
PBP	Pay Back Period	years
PDC	Parabolic Dish Collector	
PIV	Particle Image Velocimetry	-
PTC	Parabolic Trough Collector	-
PV	Photo Voltaic	-
PVT	Photo Voltaic Thermal	-
SACS	Solar Absorption Cooling System	-
SCCM	Solar Cooling Cost Metric	INR per kWh/m^2
SE	Single Effect	-
SF	Solar Fraction	-
SPBP	Simple Pay Back Period	years
STSVR	Storage Tank Specific Volume Ratio	m^3/m^2
TAC	Total Annualised Cost	INR
TR	Truncation Ratio	-
TRNSYS	Transient System Simulation	-
VAS	Vapour Absorption System	-
VCS	Vapour Compression System	-