

Investigation on Large Aperture Parabolic Trough Solar Collector

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Investigation on Large Aperture Parabolic Trough Solar Collector

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Certificate

This is to certify that the thesis entitled “**Investigation on Large Aperture Parabolic Trough Solar Collector**” being submitted by **Mr. Anish Malan** to Indian Institute of Technology Delhi in fulfillment of the requirements for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work performed by him under my guidance and supervision at **Department of Energy Science and Engineering, Indian Institute of Technology Delhi.**

The results obtained herein have not been submitted in part or in full to any other University or Institute for the award of any degree to the best of my knowledge.

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Abstract

In this study, an attempt has been made to investigate the performance of large aperture parabolic trough solar collector (PTSC). The aim of the investigation is to undertake the in-depth studies towards the improvement in the performance of the large aperture PTSC and towards its cost reduction. As the large aperture PTSC allows the design of a trough with low parasitic consumption, and lesser numbers of pylons, supporting structures, solar field piping, controls, drives and sensors which helps in reduction in costs of bill of materials. The development of the PTSC majorly governs by four parameters optical, thermal, structural, and techno-economic aspects and same has been investigated to identify the novel cost-effective large aperture PTSC configurations.

The optical analysis is performed by developing an optical model using MATLAB to obtain the flux distribution on the absorber circumference while including the limb darkening effect in the incoming solar radiation. The analysis is performed to study the effect of different Sunshape models, the number of rays, aperture diameter, and rim angle of the PTSC. Furthermore, an attempt has been made to investigate the effect of optical errors such as slope error, tracking error and receiver alignment error on the flux distribution and intercept factor.

Based on the optical analysis, it has been found that the PTSC of 9 m aperture diameter with 110 mm receiver tube is better among all the configurations considered for the analysis. The above-mentioned PTSC configuration gives an intercept factor of 0.94. It is observed that the proposed configuration has minimum effect on the intercept factor for a given receiver alignment error. Based on the optical analysis, the above-mentioned large aperture collector configuration has been identified and the same is considered for further investigations pertaining to the thermal, structural, and techno-economic analysis.

The thermal performance of the proposed large aperture PTSC has been studied in two phases i.e., thermal performance of receiver considering the conventional heat transfer fluid (HTF) such as Therminol VP1 and effect of the nanofluids on performance improvement and to minimize the circumferential temperature gradient around the absorber. The thermal analysis of the large aperture PTSC is undertaken for various operating conditions of mass flow rate (0.5 kg/s to 1.5 kg/s) and inlet fluid temperature (300 K to 650 K). The nanoparticles considered for the analysis are Al_2O_3 , Ag and a hybrid of Al_2O_3 and Ag.

Based on the thermal analysis, it has been observed that with proper choice of the HTF and/or PTSC design, it is possible to reduce the thermal gradient on absorber circumference. The least thermal gradient around the absorber circumference is observed with liquid sodium as HTF which leads to less deformation of the receiver. The maximum receiver efficiency of 82% is achieved for HTF with 8% volumetric fraction of Al_2O_3 nanoparticles. The temperature gradient across the absorber circumference also decreases with nanofluids and results show that the mean temperature observed on the absorber circumference for the Therminol VP-1, and nanofluids based on Ag (8%), Al_2O_3 & Ag (8%) and Al_2O_3 (8%) are 721 K, 707 K, 692 K and 681 K respectively.

As PTSC are deployed in the open terrains, the same are subjected to high wind speed and gust. In this view, the likely effect of the different wind load conditions on the stability of the large aperture PTSC has been undertaken. The analysis has been performed for various collector orientations (pitch angle), wind speeds and wind orientations (yaw angle). An attempt has also been made to estimate the deformation in large aperture PTSC under gravity and wind loads.

From the results of the wind load analysis, it has been observed that the collector should be designed for the drag force at 0° pitch angle for windward, whereas for stability, the lift force and pitching moment should be considered for the pitch angle of 60° at the yaw angle between

30° to 60°. The maximum force experienced by the concentrator at a maximum wind speed of 25 m/s is 6888 N at 0° pitch angle. The estimated wind loads along with the gravity load are further used to determine the deformation in the large aperture concentrator with the maximum deformation of 1.9 mm experienced for a wind speed of 25 m/s.

Based on the proposed collector configuration efforts have also been made to estimate the capital cost and identify the cost reduction avenues for large aperture (9 m) PTSC using inventory of materials approach for the Indian context. Based on the potential of reducing mass of the various subsections of the solar field, the cost of the large aperture PTSC has been estimated and the same is used to estimate the levelized cost of electricity (LCoE) for a 50 MW CSP plant for both wet and dry cooling options by considering with and without thermal energy storage (TES). It has been observed that there is a cost reduction potential of up to 25% for 9 m aperture PTSC as compared to ET based CSP plants. The lowest LCoE is estimated as INR 7.68 per kWh (1 USD = 73.29 as on 09/05/2021) for 9 m aperture PTSC, although the variation in the LCoE is enormous, increasing to INR 23.97 per kWh for the considered parameters such as location, direct normal irradiance (DNI), solar multiple (SM), and TES.

In summary, the study presents detailed investigation on several different important aspects of PTSC that include optical, thermal, structural, and techno-economic considerations. It has been identified that better manufacturing standards need to be incorporated to improve the performance of the large aperture PTSC with available receiver sizes. For the chosen collector configuration, there is cost reduction potential of approximately 25%. The results achieved through this research work provide useful insights towards cost reduction of large aperture PTSC which may help reduce the cost of electricity delivered by the PTSC based solar thermal power plants.

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सारांश

इस अध्ययन में बड़े अपर्चर पैराबोलिक ट्रफ सोलर कलेक्टर (पीटीएससी) के प्रदर्शन की जांच करने का प्रयास किया गया है। जांच का उद्देश्य बड़े अपर्चर पीटीएससी के प्रदर्शन में सुधार और इसकी लागत में कमी की दिशा में गहन अध्ययन करना है। चूंकि बड़ा अपर्चर पीटीएससी कम पैरासिटिक खपत के साथ एक ट्रफ के डिजाइन की अनुमति देता है, और कम संख्या में पाइलोंस, सहायक संरचनाएं, सौर क्षेत्र पाइपिंग, नियंत्रण, ड्राइव और सेंसर जो सामग्री के बिल की लागत को कम करने में मदद करता है। पीटीएससी का विकास प्रमुख रूप से चार मापदंडों ऑप्टिकल, थर्मल, संरचनात्मक और तकनीकी-अर्थशास्त्र पहलुओं द्वारा नियंत्रित होता है और नवीन बड़े अपर्चर पीटीएससी कॉन्फ़िगरेशन की पहचान करने के लिए इसकी जांच की गई है।

ऑप्टिकल विश्लेषण MATLAB का उपयोग करके एक ऑप्टिकल मॉडल विकसित किया जाता है ताकि आने वाले सौर विकिरण में लिम्ब डार्किनिंग प्रभाव को शामिल करते हुए अवशोषक परिधि पर फ्लक्स वितरण प्राप्त किया जा सके। विश्लेषण विभिन्न सनशेप मॉडल, किरणों की संख्या, अपर्चर व्यास और पीटीएससी के रिम कोण के प्रभाव का अध्ययन करने के लिए किया जाता है। इसके अलावा, फ्लक्स वितरण और इंटरसेप्ट फैक्टर पर ऑप्टिकल त्रुटियों जैसे ढलान त्रुटि, ट्रैकिंग त्रुटि और रिसीवर संरेखण त्रुटि के प्रभाव की जांच करने का प्रयास किया गया है।

ऑप्टिकल विश्लेषण के आधार पर, यह पाया गया है कि 110 mm रिसीवर ट्यूब के साथ 9 m अपर्चर व्यास का पीटीएससी विश्लेषण के लिए विचार किए गए सभी कॉन्फ़िगरेशन में बेहतर है। उपर्युक्त पीटीएससी कॉन्फ़िगरेशन 0.94 का इंटरसेप्ट फैक्टर देता है। यह देखा गया है कि प्रस्तावित कॉन्फ़िगरेशन का किसी दिए गए रिसीवर संरेखण त्रुटि के लिए इंटरसेप्ट फैक्टर पर न्यूनतम प्रभाव पड़ता है। ऑप्टिकल विश्लेषण

के आधार पर, उपर्युक्त बड़े एपर्चर कलेक्टर कॉन्फ़िगरेशन की पहचान की गई है और इसे थर्मल, संरचनात्मक और तकनीकी अर्थशास्त्र विश्लेषण से संबंधित आगे की जांच के लिए माना गया है।

प्रस्तावित बड़े एपर्चर पीटीएससी के थर्मल प्रदर्शन का अध्ययन दो चरणों में किया गया है, पहले कंवेन्शनल हीट ट्रांसफर फ्लुइड(एचटीएफ) जैसे कि थर्मिनॉल वीपी-1 का रिसीवर थर्मल प्रदर्शन पर अध्ययन किया गया है और इसके साथ साथ नैनोफ्लुइड्स का रिसीवर प्रदर्शन के प्रभाव और रिसीवर परिधीय तापमान के अंतर को कम करने के लिए अध्ययन किया गया है। बड़े एपर्चर पीटीएससी का थर्मल विश्लेषण प्रवाह दर (0.5 kg/s से 1.5 kg/s) और प्रवेश तरल तापमान (300 K से 650 K) की विभिन्न परिचालन स्थितियों के लिए किया गया है। विश्लेषण के लिए Al_2O_3 , Ag तथा Al_2O_3 और Ag के हाइब्रिड नैनोकणों पर विचार किया गया है।

थर्मल विश्लेषण के आधार पर, यह देखा गया है कि एचटीएफ और/या पीटीएससी डिजाइन के उचित विकल्प के साथ, रिसीवर परिधि पर थर्मल ग्रेडिएंट को कम करना संभव है। रिसीवर परिधि के चारों ओर न्यूनतम तापीय प्रवणता तरल सोडियम एचटीएफ के साथ देखी गई जिससे रिसीवर का कम विरूपण होता है। Al_2O_3 नैनोकणों के 8% वॉल्यूमेट्रिक अंश के साथ एचटीएफ के लिए 82% की अधिकतम रिसीवर दक्षता हासिल की गई है। रिसीवर परिधि में तापमान प्रवणता नैनोफ्लुइड्स के साथ भी कम हो जाती है और परिणाम बताते हैं कि थर्मिनॉल वीपी-1 Ag (8%), Al_2O_3 और Ag (8%) तथा Al_2O_3 (8%) के लिए अवशोषक परिधि पर देखा गया औसत तापमान क्रमशः 721 K, 707 K, 692 K और 681 K हैं।

चूंकि पीटीएससी को खुले इलाकों में लगाया जाता है, इसलिए वे तेज हवा की गति और झोंके के अधीन होते हैं। इस दृष्टि से, बड़े एपर्चर पीटीएससी की स्थिरता पर विभिन्न पवन भार स्थितियों का संभावित प्रभाव देखा गया है। विश्लेषण विभिन्न सांद्रक ओरिएंटेशन (पिच कोण), हवा की गति और हवा के झुकाव (याव कोण) के लिए किया गया है। गुरुत्वाकर्षण और पवन भार के कारण बड़े एपर्चर पीटीएससी में विकृति का अनुमान लगाने का भी प्रयास किया गया है।

पवन भार विश्लेषण के परिणामों से, यह देखा गया है कि कलेक्टर को विंडवर्ड के लिए 0° पिच कोण पर ड्रैग फोर्स के लिए डिज़ाइन किया जाना चाहिए, जबकि स्थिरता के लिए, लिफ्ट बल और पिचिंग मोमेंट को 60° के पिच कोण तथा यव कोण 30° से 60° के बीच में माना जाना चाहिए। 25 m/s की अधिकतम हवा की गति पर सांद्रक द्वारा अनुभव किया गया अधिकतम बल 0° पिच कोण पर 6888 N है। गुरुत्वाकर्षण भार के साथ अनुमानित पवन भार का उपयोग बड़े एपर्चर सांद्रक में विरूपण को ज्ञात करने के लिए किया गया है, जिसमें 1.9 mm की अधिकतम विकृति 25 m/s की हवा की गति के लिए अनुभव किया गया है।

प्रस्तावित कलेक्टर कॉन्फ़िगरेशन के आधार पर पूंजीगत लागत का अनुमान लगाने और भारतीय संदर्भ के लिए सामग्री दृष्टिकोण की सूची का उपयोग करके बड़े एपर्चर (9 m) पीटीएससी के लिए लागत में कमी के रास्ते की पहचान करने के प्रयास भी किए गए हैं। सौर क्षेत्र के विभिन्न उपखंडों के द्रव्यमान को कम करने की क्षमता के आधार पर, बड़े एपर्चर पीटीएससी की लागत का अनुमान लगाया गया है और इसका उपयोग 50 MW सीएसपी संयंत्र दोनों वेट एवं ड्राई कूलिंग विकल्प के साथ साथ थर्मल एनर्जी स्टोरेज (टीईएस) के साथ और बिना विचार करके बिजली की स्तरीकृत लागत (एलसीओई) का अनुमान लगाया गया है। यह देखा गया है कि ईटी आधारित सीएसपी संयंत्रों की तुलना में 9 m एपर्चर पीटीएससी के लिए लागत में 25% तक की कमी की संभावना है। 9 m एपर्चर पीटीएससी के लिए न्यूनतम एलसीओई का अनुमान INR 7.68 प्रति kWh (09/05/2021 को $1 \text{ USD} = 73.29$) के रूप में है, हालांकि एलसीओई में भिन्नता बहुत अधिक है, जो विचार किए गए मापदंडों जैसे कि स्थान, प्रत्यक्ष सामान्य विकिरण, सौर गुणक, और टीईएस के लिए INR 23.97 प्रति kWh तक बढ़ रही है।

संक्षेप में, अध्ययन पीटीएससी के कई अलग-अलग महत्वपूर्ण पहलुओं पर विस्तृत जांच प्रस्तुत करता है जिसमें ऑप्टिकल, थर्मल, संरचनात्मक और तकनीकी-अर्थशास्त्र विचार शामिल हैं। यह पहचाना गया है कि उपलब्ध रिसीवर आकारों के साथ बड़े एपर्चर पीटीएससी के प्रदर्शन में सुधार के लिए बेहतर विनिर्माण

मानकों को शामिल करने की आवश्यकता है। चुने हुए संग्राहक विन्यास के लिए, लागत में लगभग 25% कमी की संभावना है। इस शोध कार्य के माध्यम से प्राप्त परिणाम बड़े एपर्चर पीटीएससी की लागत में कमी की दिशा में उपयोगी अंतर्दृष्टि प्रदान करते हैं जो पीटीएससी आधारित सौर तापीय ऊर्जा संयंत्रों द्वारा वितरित बिजली की लागत को कम करने में मदद कर सकते हैं।

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Nomenclature

Roman letters

a	aperture (m)
b	interaction coefficient
bs	base fluid
c_p	heat capacity ($\text{J kg}^{-1} \text{K}^{-1}$)
C_d	coefficient of drag force
C_l	coefficient of lift force
C_{mz}	coefficient of pitching moment
d	absorber diameter (mm)
d_r	discount rate (%)
D_{ai}	inner diameter of absorber (mm)
D_{ao}	outer diameter of absorber (mm)
D_{gi}	inner diameter of glass cover (mm)
D_{go}	outer diameter of glass cover (mm)
f	friction factor
f_l	focal length (m)
$f_{l,avg}$	average surface to focus path length (m)
F_x	horizontal force (N)
F_y	vertical force (N)
G_k	turbulent kinetic energy generation rate ($\text{m}^2 \text{s}^{-2}$)
h	heat transfer coefficient ($\text{W m}^{-2} \text{K}^{-1}$)
I	relative intensity
I_b	irradiance (W m^{-2})

I_o	intensity at the centre of Sun image
k_{eff}	annulus air thermal conductivity (effective) ($W\ m^{-1}\ K^{-1}$)
k_{std}	annulus air thermal conductivity (standard) ($W\ m^{-1}\ K^{-1}$)
l	length of collector (m)
m	mass (kg)
$\dot{m}$	mass flow rate ($kg\ s^{-1}$)
n	number of years
Nu	Nusselt number
nf	nanofluid
np	nanoparticles
P_a	pressure of annulus gas (Pa)
Pr	Prandtl number
ΔP	pressure drop (Pa)
Q_{total}	total available energy (W)
Q_{useful}	useful heat gain (W)
r	arbitrary radius in the Sun image
Re	Reynolds number
R_o	size of the Sun image on a perpendicular plane (m)
R'_o	size of the Sun image on preceding perpendicular plane (m)
T_{amb}	ambient temperature (K)
T_{ao}	surface temperature of outer absorber (K)
T_{gi}	surface temperature of inner glass cover (K)
T_{in}	inlet temperature of working fluid (K)
T_{fm}	temperature of mean fluid (K)
T_{out}	temperature at outlet of receiver (K)

T_r	mean temperature of receiver (K)
T_{sky}	temperature of sky (K)
u	velocity ($m\ s^{-1}$)
u_{ref}	terrain wind speed ($m\ s^{-1}$)
V	reference wind speed ($m\ s^{-1}$)
W_p	pumping power (W)
x, y, z	cartesian coordinates
y	distance from ground (m)
y_{ref}	atmospheric boundary layer height (m)

Greek symbols

k	kinetic energy ($m^2\ s^{-2}$)
Θ_1, Θ_2	extremities of the ideal conical reflected ray ($^\circ$)
Θ_3, Θ_4	extremities of the conical reflected ray for the dislocated receiver ($^\circ$)
θ_s	half angle subtended by sun ($^\circ$)
δ	annulus gas molecular diameter (cm)
δ_s	slope error (mrad)
δ_t	tracking error (mrad)
δ_x, δ_y	receiver alignment error (mm)
μ	dynamic viscosity of working fluid (pa s)
μ_t	turbulent viscosity of working fluid (pa s)
ε	turbulent dissipation rate ($m^2\ s^{-3}$)
ε_a	absorber emissivity
ε_g	glass cover emissivity
ρ	density ($kg\ m^{-3}$)

Ψ	rim angle (°)
λ	thermal conductivity of working fluid ($\text{W m}^{-2} \text{K}^{-1}$)
ν	kinematic viscosity of working fluid ($\text{m}^2 \text{s}^{-1}$)
γ	intercept factor
α_a	absorber absorptance
α_g	glass cover absorptance
τ_z	pitching moment (N m)
η_{th}	thermal efficiency (%)
ϕ	volumetric fraction (%)
σ_T	Prandtl number (turbulent)
$\sigma_k, \sigma_\epsilon$	Prandtl numbers (turbulent) for the diffusion of k and ϵ
C_μ, C_1, C_2	turbulence model coefficients

Subscripts

b	base fluid
p	nanoparticle
w	wind

Abbreviations

ABL	atmospheric boundary layer
AC	annual cost
AE	annual electricity generation
AOA	angle of attack
AOM	annual operation and maintenance cost.
CERC	Central Electricity Regularity Commission
CFD	computational fluid dynamics
CR	child ray

CSP	concentrated solar power
CTR	central tower receiver
CTM	camera target method
DA	depreciation amount
DNI	direct normal irradiance
EPC	engineering, procurement, and construction
ESS	engineering equation solver
ET	Euro Trough
FVM	finite volume method
GCR	geometrical concentration ratio
HS	heated steam
HTF	heat transfer fluid
LCoE	levelized cost of electricity
LCR	local concentration ratio
LFR	linear Fresnel reflector
LI	interest on loan
LP	loan principal component
MCRT	Monte Carlo ray tracing
MS	molten salt
NSDRB	national solar resource database
PB	power block
PCR	principle cost remaining
PDC	parabolic dish collector
PP	perpendicular plane
PTSC	parabolic trough solar collector

RE	return on equity
RMS	root mean square
SAM	system advisor model
SCA	solar collector assembly
SCE	solar collector element
SEGS	solar energy generating systems
SF	solar field
SST	shear stress transport
TES	thermal energy storage
TO	thermic oil
USD	united stated dollar
WCI	working capital interest