

**DEVELOPMENT OF NOVEL INVERSE METHODS FOR SOLAR PV
SYSTEM AND CONTINUOUS CASTING PROCESS**

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DEVELOPMENT OF NOVEL INVERSE METHODS FOR SOLAR PV SYSTEM AND CONTINUOUS CASTING PROCESS

by

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CERTIFICATE

I am satisfied that the thesis entitled “**DEVELOPMENT OF NOVEL INVERSE METHODS FOR SOLAR PV SYSTEM AND CONTINUOUS CASTING PROCESS**” presented by **Mr. Ananda Srinivas Vaka** is worthy of the consideration for the award of the degree of **DOCTOR OF PHILOSOPHY** and is a record of the original bona fide research work carried out by him under my guidance and supervision, and the results contained in it have not been submitted in part or full to any other university or institute for the award of any degree/diploma.

I certify that he has pursued the prescribed course of research.

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Ananda Srinivas Vaka

ABSTRACT

Many engineering and Industrial applications nowadays involve complex processes which require accurate and speedy estimation of important boundary conditions, properties and process parameters for analysis. The design, as well as the operation, and the quality assessment and control of various processes occurring in many thermal applications, often require precise knowledge of boundary conditions, properties and process parameters. In some situations, measurement of these quantities is very difficult because of unapproachable locations or sluggish measuring techniques. At present, however, the technique of the inverse heat transfer (IHT) has offered a convenient substitute to estimate the unknown quantities accurately and instantaneously, which significantly reduce the resources. In this work, some of the latest and efficient algorithms, one deterministic algorithm, Conjugate Gradient Method (CGM), and two meta-heuristic algorithms, Ant Colony Optimization (ACO) and Salp Swarm Algorithm (SSA) are used to estimate the unknowns. One distinctive combination of predicting the characteristic profile of the variable boundary condition and estimating the corresponding profile parameters is also presented. This innovative methodology is conceptualised, and the corresponding codes are indigenously developed by the author. Inverse heat transfer problem (IHTP) techniques are good alternatives for the complex problems and in this work, two classes of complex problems, roof-mounted solar PV power plants and continuous casting process through billet, slab and thin-slab moulds are analysed.

Accurate quantification of variable properties and site-specific process parameters of roof-mounted solar PV power plants are essential for the design and development of the power plant as well as for the operation and maintenance and capacity improvement/reclaim of the power plant. In this work, a novel inverse heat transfer technique based on an efficient optimization method, Salp Swarm Algorithm (SSA), has been used to estimate the unknown properties and process parameters. This methodology has been proven to be efficient and has not yet been used for thermal applications which use limited on-site plant recorded data and consumes relatively less computational and experimental resources. Numerical and experimental analyses are carried out for the representative periods and the representative days. The observed results indicate that the location-specific process parameters can be estimated with reasonable

accuracy and these results can be used to estimate the module temperature which, in turn, is used for an accurate estimation of power generated using temperature coefficients and healthiness of the system. The proposed methodology is simple to execute, uses only limited experimental data and is recommended for studies aimed towards estimating the unknown properties and process parameters.

Inverse techniques take exorbitantly more time to predict the boundary conditions such as heat flux of a mould and most of the time, the results are fluctuating. In industrial casting applications, estimation of the thermal state of the mould using traditional methods, does not give the correct results within the stipulated time. A novel and innovative methodology of combining the theoretical and practical knowledge coupled with a new inverse technique is demonstrated in the present study to estimate the variable heat flux of a billet mould. This unique method predicts the characteristic profile of the unknown heat flux initially using the available knowledge from the literature or the function estimation IHTP method, CGM and then, estimates the corresponding profile parameters using a few sets of experimental observations, using a meta-heuristic algorithm, SSA.

Inverse heat transfer methods are typically employed to estimate the heat flux variation by assuming a one-dimensional variation of heat flux along the casting direction. The assumption of one-dimensional heat flux often leads to significant error, especially in determining the corner heat flux which affects the shrinkage behaviour and thereby, the quality of the products of casting. Prior studies have recognized this error and assumed this error of heat flux as a constant deviation to account for the longitudinal and transverse variation of heat flux. In this research work, a novel methodology has been presented to predict the variable interfacial heat flux of a three-dimensional mould domain by assuming the general quadratic profile for heat flux variation and estimating the parameters of a characteristic heat flux profile with the SSA. This methodology uses only the limited experimental data or on-site plant recorded data and hence, it consumes relatively less computational and experimental resources. Representative cases of billet and slab moulds have been considered for numerical analysis using experimental data obtained by the industries. Results indicate that the mould corner heat flux is considerably different from that of the assumed value of 67 % of the literature with deviation reaching as high as 56 % near the meniscus for a slab casting mould.

Subsequently, the methodology is extended to the thin slab continuous casting mould for the estimation of heat flux at the interface of the mould and liquid metal. The mould considered in this work is an industrial funnel-shaped mould having a complex arrangement of cooling holes and slots. Significant variations of heat flux are observed along the casting direction, as well as in other directions. The non-linear behaviour of the heat flux profile is captured well in the current study, which also leads to a better estimation of the thermal characteristics in the solidifying strand. Heat flux variation as high as 77% relative to wide face centre and 85% relative to the maximum heat flux zone was observed in the corner region. This study also explored the minimum number of sensors to be placed inside the funnel-shaped mould for accurate estimation of the interfacial heat flux.

सार

कई इंजीनियरिंग और औद्योगिक अनुप्रयोगों में आजकल जटिल प्रक्रियाएं शामिल हैं जिनके विश्लेषण के लिए महत्वपूर्ण सीमा स्थितियों, गुणों और प्रक्रिया मापदंडों के सटीक और त्वरित अनुमान की आवश्यकता होती है। कई थर्मल अनुप्रयोगों में होने वाली विभिन्न प्रक्रियाओं के डिजाइन, संचालन और गुणवत्ता नियंत्रण के लिए अक्सर सीमा स्थितियों, गुणों और प्रक्रिया मापदंडों के सटीक ज्ञान आवश्यक हैं। जैसे, दुर्गम स्थानों या सुस्त माप तकनीकों के कारण इन मात्राओं का मापन बहुत कठिन होता है। वर्तमान में, हालांकि, उलटा गर्मी हस्तांतरण समस्या (आईएचटीपी) की तकनीकों ने अज्ञात मात्राओं का सटीक और तत्काल अनुमान लगाने के लिए एक सुविधाजनक विकल्प की पेशकश की है, जो प्रयोगात्मक संसाधनों को काफी कम कर देता है। इस काम में, कुछ नवीनतम और कुशल एल्गोरिदम, एक नियतात्मक एल्गोरिथ्म, संयुग्मित ढाल विधि (सीजीएम) और दो मेटा-हेयुरिस्टिक एल्गोरिदम, चींटी कॉलोनी अनुकूलन (एसीओ) और साल्प झुंड एल्गोरिदम (एसएसए) का उपयोग अज्ञात मात्राओं का अनुमान लगाने के लिए किया गया है। चर सीमा की स्थिति की विशेषता प्रोफ़ाइल की भविष्यवाणी करने और संबंधित प्रोफ़ाइल मापदंडों का अनुमान लगाने का एक अनूठा संयोजन भी प्रस्तुत किया गया है। इस नवीन पद्धति की अवधारणा की गई है और संबंधित कोड लेखन-द्वारा स्वदेशी रूप से विकसित किए गए हैं। इनवर्स हीट ट्रांसफर प्रॉब्लम (आईएचटीपी) तकनीक जटिल समस्याओं के लिए अच्छा-विकल्प है और इस काम में जटिल समस्याओं के दो वर्ग, रूफ-माउंटेड सोलर पीवी पावर प्लांट और बिलेट, स्लैब और थिन-स्लैब मोल्ड्स के माध्यम से निरंतर कास्टिंग प्रक्रिया का विश्लेषण किया गया है।

छत पर लगे सौर पीवी बिजली संयंत्रों के परिवर्तनशील गुणों और स्थान-विशिष्ट प्रक्रिया मापदंडों की सटीक मात्रा का ठहराव बिजली संयंत्र के डिजाइन और विकास के साथ-साथ बिजली संयंत्र के संचालन और अनुरक्षण (रखरखाव) और क्षमता में सुधार / पुनः प्राप्त करने के लिए आवश्यक है। इस काम में, अज्ञात गुणों और प्रक्रिया मापदंडों का अनुमान लगाने के लिए एक कुशल अनुकूलन विधि, साल्प स्वार्म एल्गोरिथ्म (एसएसए) पर आधारित एक क्रियाविधि-उलटा गर्मी हस्तांतरण तकनीक का उपयोग किया गया है। यह पद्धति कुशल साबित हुई है और अभी तक थर्मल अनुप्रयोगों के लिए उपयोग नहीं की गई है जो सीमित ऑन-साइट प्लांट रिकॉर्ड किए गए डेटा का उपयोग करते हैं और

अपेक्षाकृत कम कम्प्यूटेशनल और प्रयोगात्मक संसाधनों का उपभोग करते हैं। प्रतिनिधि अवधि और प्रतिनिधि दिनों के लिए संख्यात्मक और प्रयोगात्मक विश्लेषण किए गए हैं। देखे गए परिणामों से संकेत मिलता है कि स्थान-विशिष्ट प्रक्रिया मापदंडों का अनुमान उचित सटीकता के साथ लगाया जा सकता है और इन परिणामों का उपयोग मॉड्यूल तापमान का अनुमान लगाने के लिए किया जा सकता है जो बदले में तापमान गुणांक और सिस्टम की स्वस्थता का उपयोग करके उत्पन्न शक्ति के सटीक अनुमान के लिए उपयोग किया जाता है। प्रस्तावित कार्यप्रणाली लागू करने के लिए सरल है, केवल सीमित प्रयोगात्मक डेटा का उपयोग करता है तथा अज्ञात गुणों और प्रक्रिया मापदंडों का अनुमान लगाने के उद्देश्य से अध्ययन के लिए अनुशंसित है।

व्युत्क्रम तकनीकें सीमा की स्थितियों की भविष्यवाणी करने में अत्यधिक समय लेती हैं जैसे कि एक साँचे का ताप प्रवाह और अधिकांश समय साथ ही परिणाम में उतार-चढ़ाव भी होता है। औद्योगिक कास्टिंग अनुप्रयोगों में पारंपरिक तरीकों का उपयोग करके मोल्ड की थर्मल स्थिति का आकलन निर्धारित समय के भीतर सही परिणाम नहीं देता है। एक बिलेट मोल्ड के परिवर्तनीय ताप प्रवाह का अनुमान लगाने के लिए वर्तमान अध्ययन में एक नई आईएचटीपी तकनीक के साथ सैद्धांतिक और व्यावहारिक ज्ञान के संयोजन की एक नवीन और अभिनव पद्धति का प्रदर्शन किया गया है। यह अनूठी विधि पहले साहित्य या फ़ंक्शन अनुमान आईएचटीपी विधि, सीजीएम से पहले से उपलब्ध ज्ञान का उपयोग करके अज्ञात ऊष्मा प्रवाह की विशेषता प्रोफ़ाइल की भविष्यवाणी करती है और फिर, प्रयोगात्मक टिप्पणियों के कुछ सेटों का तथा एसएसए का उपयोग करके संबंधित प्रोफ़ाइल मापदंडों का अनुमान लगाती है।

उल्टा गर्मी हस्तांतरण विधियों को आम तौर पर कास्टिंग दिशा के साथ गर्मी प्रवाह की एक-आयामी भिन्नता मानकर गर्मी प्रवाह भिन्नता की भविष्यवाणी करने के लिए नियोजित किया जाता है। एक-आयामी गर्मी प्रवाह की धारणा अक्सर विशेष रूप से कोने के गर्मी प्रवाह को निर्धारित करने में महत्वपूर्ण त्रुटि की ओर ले जाती है जो संकोचन व्यवहार को प्रभावित करती है और इस प्रकार, कास्टिंग के उत्पादों की गुणवत्ता भी प्रभावित होती है। पूर्व के अध्ययनों ने इस त्रुटि को मान्यता दी है और ऊष्मा प्रवाह की इस त्रुटि को ऊष्मा प्रवाह के अनुदैर्ध्य और अनुप्रस्थ भिन्नता के लिए एक निरंतर विचलन के रूप में माना है। इस शोध कार्य में, ऊष्मा प्रवाह भिन्नता के लिए सामान्य द्विघात प्रोफ़ाइल को मानकर और साल्ट झुंड एल्गोरिथम (एसएसए) के साथ एक विशेषता गर्मी प्रवाह प्रोफ़ाइल के मापदंडों का

अनुमान लगाकर एक तीन-आयामी मोल्ड डोमेन के परिवर्तनशील इंटरफेशियल हीट फ्लक्स की भविष्यवाणी करने के लिए एक क्रियाविधि पद्धति प्रस्तुत की गई है। यह पद्धति केवल सीमित प्रयोगात्मक डेटा या ऑन-साइट प्लांट रिकॉर्ड किए गए डेटा का उपयोग करती है और इसलिए यह अपेक्षाकृत कम कम्प्यूटेशनल और प्रयोगात्मक संसाधनों का उपभोग करती है। उद्योगों द्वारा प्राप्त प्रयोगात्मक डेटा का उपयोग करके संख्यात्मक विश्लेषण के लिए बिलेट और स्लैब मोल्ड के प्रतिनिधि मामलों पर विचार किया गया है। परिणामों से संकेत मिलता है कि मोल्ड कॉर्नर हीट फ्लक्स साहित्य के ६७% के अनुमानित संख्या से काफी भिन्न है, जिसमें स्लैब कास्टिंग मोल्ड के लिए मेनिस्कस के पास विचलन ५६% तक पहुंच गया है।

इसके बाद मोल्ड के गर्म चेहरों पर गर्मी प्रवाह की भविष्यवाणी के लिए कार्यप्रणाली को पतली स्लैब निरंतर कास्टिंग मोल्ड तक बढ़ाया गया है। इस काम में माना जाने वाला औद्योगिक साँचा एक फ़नल के आकार का साँचा है जिसमें शीतलन स्लॉट और छेद की एक जटिल व्यवस्था होती है। कास्टिंग दिशा तथा चौड़ाई के साथ गर्मी प्रवाह के महत्वपूर्ण बदलाव देखे गए हैं। वर्तमान अध्ययन में हीट फ्लक्स प्रोफाइल के गैर-रैखिक व्यवहार को अच्छी तरह से पकड़ लिया गया है, जिससे ठोस स्ट्रैंड में थर्मल विशेषताओं का बेहतर अनुमान भी होता है। वाइड फेस सेंटर के सापेक्ष हीट फ्लक्स भिन्नता ७७% और अधिकतम हीट फ्लक्स ज़ोन के सापेक्ष ८५% कोने क्षेत्र में देखी गई। इस अध्ययन ने इंटरफेशियल बाउंड्री हीट फ्लक्स के सटीक अनुमान के लिए फ़नल के आकार के मोल्ड के अंदर रखे जाने वाले सेंसर की न्यूनतम संख्या का भी पता लगाया।

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NOMENCLATURE

Roman symbols

a	absorptivity coefficient, [$\text{m}^2\text{K/W}$]
A	area [m^2]
c	parameters/vectors of SSA
C	heat capacity [J/K]
C_p	specific heat [J/(kg K)]
d	thickness [m], Direction of descent, the index number of model parameters
D	diameter
f	objective function [$^\circ\text{C}$]
F	Position of food [-]
G	Solar Irradiance [W/m^2]
h	heat transfer coefficient [$\text{W/(m}^2\text{K)}$]
H	height of the meniscus from bottom
H_1	height of mould top from the meniscus
k	conductivity [W/(mK)]
L	characteristic length [m]
lb	lower bound [-]
g_p	Heat source strength [W/m]
Gr	Grashof number [-]
M	Number of ants
N	Number of iterations, number of layers of the PV module [-]
Nu	Nusselt number [-]
P	Total number of time intervals [-], total number of sensors [-]
Pr	Prandtl number [-]
q	heat transfer rate [W]
q_s''	heat flux [W/m^2]
Q	number of salps [-]
Ra	Rayleigh number [-]
t	time [s]
T	temperature [$^\circ\text{C}$] or [K]
ub	upper bound [-]
v	velocity [m/s]

w	wind speed [m/s]
K	Number of Basis functions in CGM
NF	Narrow face
Pr	Prandtl number
Re	Reynolds number
WF	Wide face
x, y, z	Co-ordinate axes

Greek symbols

α	absorptivity [-] / narrowing parameter [-]
β	the angle of the solar PV module to the vertical direction [-] / Evaporation rate / search step size
γ	Elevation angle of the sun [-] / Conjugate coefficient
δ	Dirac delta function
δT	The temperature difference between the sky and the panel [°C]
ΔT	The temperature difference between front and back of the panel [°C]
ε	emissivity [-] / tolerance
ρ	density [kg/m ³]
σ	Stefan-Boltzmann constant [W/m ² /K ⁴], Standard Deviation of measurements
ν	kinematic viscosity [m ² /s]
λ	Lagrange multiplier
μ	Dynamic viscosity [kg/m/s]
τ	strength of pheromone

Subscripts

a	adjustment coefficient, ambient
act	actual
air	air
$back$	back surface of the panel
br	back surface to roof
bs	back surface to sky
$casting$	casting
$conv$	convective
cr	critical

<i>f</i>	final
<i>film</i>	film layer
<i>forced</i>	forced convection
<i>fr</i>	front surface to roof
<i>front</i>	front surface of the panel
<i>free</i>	free convection
<i>fs</i>	front surface to sky
<i>h</i>	horizontal plane, hydraulic
<i>g</i>	heat source distance
<i>i</i>	initial
<i>in</i>	input
<i>j</i>	dimension index
<i>lw</i>	long-wave
<i>loss</i>	loss
<i>max</i>	maximum
<i>mod</i>	PV module
<i>out</i>	output
<i>p</i>	time interval index, sensor distance
<i>r</i>	roof of the building
<i>ref</i>	reference
<i>s</i>	source
<i>sky</i>	sky
<i>surface</i>	surface of the panel
<i>t</i>	thermal
<i>T</i>	Total
<i>w</i>	Wind, water
<i>l</i>	core parameter of SSA
2,3	random vectors of SSA

Superscripts

<i>back</i>	back surface of panel
<i>front</i>	front surface of panel
<i>i</i>	salp index
<i>N</i>	Number of salps