

**THERMO-MECHANICAL MODELLING AND
OPTIMIZATION OF POROUS VOLUMETRIC SOLAR
RECEIVERS**

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by

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Submitted

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CERTIFICATE

I am satisfied that the thesis entitled “**THERMO-MECHANICAL MODELLING AND OPTIMIZATION OF POROUS VOLUMETRIC SOLAR RECEIVERS**” presented by **Ms. SONIKA SHARMA** is worthy of the consideration for the award of the degree of **DOCTOR OF PHILOSOPHY** and is a record of the original bonafide research work carried out by her 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 award of any degree/diploma. I certify that she has pursued the prescribed course of research.



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ABSTRACT

Harnessing solar energy in an efficient and effective way is crucial to fulfilling the ever increasing energy demands in a sustainable manner. Concentrated Solar Power (CSP) technology enables the collection of solar energy using mirror concentrators, which focus it over a small area of receivers, leading to efficient capture and utilization of solar energy. Among the various receiver types, Volumetric Solar Receivers (VSRs) are particularly well-suited for high-temperature applications. The porous structure of the VSRs helps in deeper absorption of solar energy in the receiver volume, thereby reducing the re-radiation losses at elevated temperatures. The heat transfer fluid gets heated while flowing through the pores of the receiver, thus converting solar energy into thermal energy. This thermal energy can be subsequently used for applications like electricity production and various industrial applications. However, VSRs face challenges such as lower outputs, thermal hotspots and material failure due to high flux exposures, non-uniform temperatures and thermal gradients and working cycles. Therefore, it is necessary to thoroughly investigate the receiver's performance and explore ways to enhance performance without compromising the mechanical safety of the receiver.

The present research is focussed on investigating the Thermal-Hydraulic-Mechanical (THM) performance of a VSR subjected to steady and transient concentrated solar fluxes. Key performance indicators such as air outlet temperature, pressure drop across the VSR and Failure Index are used to evaluate the thermal, hydraulic and mechanical performance, respectively. A coupled thermo-mechanical model is developed to determine the THM performance of VSR. Additionally, parametric studies have been conducted to understand the effect of various parameters, including porosity and pore size of the porous structure, inlet velocity, absorber length, and the degree of non-uniformity in the incident solar flux on the VSR performance. It is observed that higher porosities and pore sizes show better mechanical safety and promise safer operation. The near-wall region at the inlet is found to be most critical for absorber safety.

The optimization of these design parameters such as porosity, pore size, inlet velocity, and receiver length is also conducted using Genetic Algorithm (GA) to determine the optimum parameter values. To minimize the optimization time and facilitate quick design changes, a surrogate model is first developed using Deep Neural Networks (DNN). The dataset for the model is obtained through actual numerical simulations, and a systematic study is performed to identify the most suitable model architecture and training algorithm suitable for accurately

predicting the THM performance parameters. Based on it, the trained DNN model with 5 hidden layers and 20 neurons per layer is selected to predict the THM performance of the VSR. The actual simulations are replaced by the DNN model predictions during the optimization process, significantly reducing the optimization time and computational resources. A multi-objective optimization problem is formulated with the objective of maximizing air outlet temperature and minimizing pressure drop. The problem is constrained by the constraint of a maximum Failure Index less than the material failure limit to ensure the optimized design parameters maintain receiver safety while enhancing the VSR performance. A comparative study is done to assess the effectiveness of the DNN-GA integrated approach in reducing the optimization time. The DNN-GA integrated approach is found to be 524 times faster than the conventional direct approach. Further studies are conducted to optimize the structural parameters (porosity and pore size) for various inlet velocities and absorber lengths. Simultaneous optimization of design parameters is also conducted to evaluate the performance enhancement in the receiver. The results are presented as Pareto optimal solutions, and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is implemented to select design parameters from these Pareto optimal solutions as per the requirements of the designer. The results indicate that the optimum values for porosity, pore size, and absorber length are in the range of 0.9-0.93, 2-4 mm, and 0.01-0.06 m, respectively, when all variables are optimized simultaneously. Furthermore, the optimal input velocity is observed to be close to the lower bound of 0.4 m/s while the corresponding maximum failure index varies from 0.346 to 0.836, indicating mechanically safe configurations.

The effectiveness of functionally graded porous structure in enhancing the THM performance of a VSR is also analyzed in the present work. The numerical model is extended to implement linear spatial variation of porosity and pore size in radial and axial directions, resulting in radial and axial graded structures. Additionally, a combination of radial and axial variation is used to create bidirectional variations. Numerical simulations are performed to determine the THM performance of these graded configurations and compared with best-performing uniform configuration. The top performing configurations from each category (axial, radial and bidirectional) are further compared across a range of inlet velocities and absorber lengths to determine the overall best configuration. It is observed that *a-PI-SC*, *r-PC-SI* and *r-PD+a-SI* are the best performing configurations of each category, i.e., axial, radial and bidirectional, in the porosity range of 0.9 - 0.95 and pore size range of 2 - 4 mm. Overall, *r-PD+a-SI* configuration outperforms among all the graded structures with the second highest

PEC and highest *FI Ratios*. It shows an increase of 8.96 % in T_b and a decrease of 22.7 % and 4 % in *FI* and ΔP , respectively.

As the VSR experiences transient solar fluxes while operating, a transient thermo-mechanical model is also developed to analyze the dynamic VSR performance. The variation of THM performance indicators over time is investigated during different operational phases of VSR, including start-up, shutdown, daily clear sky operation and cloud passing. The air outlet temperature varied by nearly 370 K during clear-sky operation, potentially leading to disruption for downstream operations. It highlights the necessity of dynamic control. The effect of different startup and shut down durations on the THM performance is also investigated. Smaller start-up and shut-down periods were observed to result in higher temperature and FI variations and vice-versa. Additionally, the effect of cloud transmissivity and solid matrix structure, such as porosity and pore size, on the solid temperature distribution and Failure Index is analyzed. Clouds with zero transmissivity were observed to cause the worst temperature gradients and the highest FI peaks.

The results of this work provide valuable insights for better designing VSRs and selecting appropriate parameters to enhance performance, resulting in higher outputs, lower pumping power and higher mechanical safety. While specific results can vary based on the case, these observations serve as a valuable guide for general design choices. For uniform configurations, porosities higher than 0.85 and pore sizes of 2 mm or larger provide suitable trade-off for efficient and safer configurations. Simultaneous optimization further refines this range to a porosity of 0.9-0.93 and pore sizes of 2-4 mm. In graded configurations with linear gradations within a porosity range of 0.9-0.95 and pore size range of 2-4 mm, the bidirectional (*r-PD+a-SI*) configuration delivers the best results, followed by the axial (*a-PI-SC*) and radial (*r-PC-SI*) configurations.

Keywords: Concentrated solar energy; Volumetric solar receiver; Porous media; Thermo-Mechanical modelling; Deep Neural Networks; Multi-objective optimization; Genetic Algorithm, Graded porous structure

सार

लगातार बढ़ती ऊर्जा मांगों को टिकाऊ तरीके से पूरा करने के लिए सौर ऊर्जा का कुशल और प्रभावी तरीके से उपयोग करना महत्वपूर्ण है। सांद्रित सौर ऊर्जा (CSP) तकनीक दर्पण सांद्रक का उपयोग करके सौर ऊर्जा के संग्रह को सक्षम बनाती है, जो इसे रिसेवर के एक छोटे से क्षेत्र पर केंद्रित करती है, जिससे सौर ऊर्जा का कुशल संग्रहण और उपयोग होता है। विभिन्न रिसेवर प्रकारों में, वॉल्यूमेट्रिक सोलर रिसेवर (VSR) विशेष रूप से उच्च तापमान अनुप्रयोगों के लिए उपयुक्त हैं। VSR की छिद्रपूर्ण संरचना रिसेवर वॉल्यूम में सौर ऊर्जा के गहन अवशोषण में मदद करती है, जिससे ऊंचे तापमान पर पुनः विकिरण हानि कम हो जाती है। ऊष्मा स्थानांतरण द्रव रिसेवर के छिद्रों में बहते समय गर्म हो जाता है, इस प्रकार सौर ऊर्जा को तापीय ऊर्जा में परिवर्तित कर देता है। इस तापीय ऊर्जा का उपयोग बाद में बिजली उत्पादन और विभिन्न औद्योगिक अनुप्रयोगों जैसे अनुप्रयोगों के लिए किया जा सकता है। हालाँकि, VSR को कम आउटपुट, थर्मल हॉटस्पॉट और उच्च फ्लक्स एक्सपोज़र, गैर-समान तापमान और थर्मल ग्रेडिएंट और कार्य चक्र के कारण सामग्री की विफलता जैसी चुनौतियों का सामना करना पड़ता है। इसलिए, रिसेवर के प्रदर्शन की पूरी तरह से जांच करना और रिसेवर की यांत्रिक सुरक्षा से समझौता किए बिना प्रदर्शन को बढ़ाने के तरीकों का पता लगाना आवश्यक है।

वर्तमान शोध स्थिर और क्षणिक संकेंद्रित सौर प्रवाह के अधीन VSR के थर्मल-हाइड्रोलिक-मैकेनिकल (THM) प्रदर्शन की जांच पर केंद्रित है। प्रमुख प्रदर्शन संकेतक जैसे एयर आउटलेट तापमान, VSR में दबाव ड्रॉप और विफलता सूचकांक का उपयोग क्रमशः थर्मल, हाइड्रोलिक और मैकेनिकल प्रदर्शन का मूल्यांकन करने के लिए किया जाता है। VSR के THM प्रदर्शन को निर्धारित करने के लिए एक युग्मित थर्मो-मैकेनिकल मॉडल विकसित किया गया है। इसके अतिरिक्त, VSR प्रदर्शन पर छिद्रपूर्ण संरचना की सरंध्रता और छिद्र आकार, इनलेट वेग, अवशोषक लंबाई और घटना सौर प्रवाह में गैर-एकरूपता की डिग्री सहित विभिन्न मापदंडों के प्रभाव को समझने के लिए पैरामीट्रिक अध्ययन आयोजित किए गए हैं। यह देखा गया है कि उच्च छिद्र और छिद्र आकार बेहतर यांत्रिक सुरक्षा दिखाते हैं और सुरक्षित संचालन का वादा करते हैं। इनलेट पर दीवार के पास का क्षेत्र अवशोषक सुरक्षा के लिए सबसे महत्वपूर्ण पाया गया है।

इन डिज़ाइन मापदंडों जैसे छिद्रता, छिद्र आकार, इनलेट वेग और रिसेवर की लंबाई का अनुकूलन भी इष्टतम पैरामीटर मान निर्धारित करने के लिए जेनेटिक एल्गोरिदम (GA) का उपयोग करके किया जाता है। अनुकूलन समय को कम करने और त्वरित डिज़ाइन परिवर्तनों की सुविधा के लिए, सबसे पहले डीप न्यूरल नेटवर्क्स (DNN) का उपयोग करके एक सरोगेट मॉडल विकसित किया गया है। मॉडल

के लिए डेटासेट वास्तविक संख्यात्मक सिमुलेशन के माध्यम से प्राप्त किया जाता है, और THM प्रदर्शन मापदंडों की सटीक भविष्यवाणी के लिए उपयुक्त सबसे उपयुक्त मॉडल वास्तुकला और प्रशिक्षण एल्गोरिदम की पहचान करने के लिए एक व्यवस्थित अध्ययन किया जाता है। इसके आधार पर VSR के THM प्रदर्शन की भविष्यवाणी करने के लिए 5 छिपी परतों और प्रति परत 20 न्यूरॉन्स के साथ प्रशिक्षित DNN मॉडल का चयन किया जाता है। अनुकूलन प्रक्रिया के दौरान वास्तविक सिमुलेशन को DNN मॉडल पूर्वानुमानों द्वारा प्रतिस्थापित किया जाता है, जिससे अनुकूलन समय और कम्प्यूटेशनल संसाधनों में काफी कमी आती है। वायु आउटलेट तापमान को अधिकतम करने और दबाव में गिरावट को कम करने के उद्देश्य से एक बहुउद्देश्यीय अनुकूलन समस्या तैयार की गई है। VSR प्रदर्शन को बढ़ाने के दौरान अनुकूलित डिज़ाइन पैरामीटर रिसीवर सुरक्षा बनाए रखने को सुनिश्चित करने के लिए सामग्री विफलता सीमा से कम अधिकतम विफलता सूचकांक की बाधा से समस्या बाधित होती है। अनुकूलन समय को कम करने में DNN-GA एकीकृत दृष्टिकोण की प्रभावशीलता का आकलन करने के लिए एक तुलनात्मक अध्ययन किया जाता है। DNN-GA एकीकृत दृष्टिकोण पारंपरिक प्रत्यक्ष दृष्टिकोण की तुलना में 524 गुना तेज पाया गया है। विभिन्न इनलेट वेगों और अवशोषक लंबाई के लिए संरचनात्मक मापदंडों (छिद्रता और छिद्र आकार) को अनुकूलित करने के लिए आगे के अध्ययन आयोजित किए जाते हैं। रिसीवर में प्रदर्शन वृद्धि का मूल्यांकन करने के लिए डिज़ाइन मापदंडों का एक साथ अनुकूलन भी किया जाता है। परिणामों को पेरेंटो इष्टतम समाधान के रूप में प्रस्तुत किया जाता है, और डिज़ाइनर की आवश्यकताओं के अनुसार इन पेरेंटो इष्टतम समाधानों से डिज़ाइन मापदंडों का चयन करने के लिए आदर्श समाधान (TOPSIS) की समानता द्वारा वरीयता क्रम की तकनीक लागू की जाती है। नतीजे बताते हैं कि छिद्रता, छिद्र आकार और अवशोषक लंबाई के लिए इष्टतम मान क्रमशः 0.9-0.93, 2-4 मिमी और 0.01-0.06 मीटर की सीमा में हैं, जब सभी चर एक साथ अनुकूलित होते हैं। इसके अलावा, इष्टतम इनपुट वेग 0.4 मीटर/सेकेंड की निचली सीमा के करीब देखा जाता है, जबकि संबंधित अधिकतम विफलता सूचकांक 0.346 से 0.836 तक भिन्न होता है, जो यांत्रिक रूप से सुरक्षित कॉन्फ़िगरेशन को दर्शाता है।

वर्तमान कार्य में VSR के THM प्रदर्शन को बढ़ाने में कार्यात्मक रूप से वर्गीकृत छिद्रपूर्ण संरचना की प्रभावशीलता का भी विश्लेषण किया गया है। रेडियल और अक्षीय दिशाओं में छिद्रता और छिद्र आकार के रैखिक स्थानिक भिन्नता को लागू करने के लिए संख्यात्मक मॉडल का विस्तार किया जाता है, जिसके परिणामस्वरूप रेडियल और अक्षीय वर्गीकृत संरचनाएं होती हैं। इसके अतिरिक्त, रेडियल और अक्षीय भिन्नता के संयोजन का उपयोग द्विदिशात्मक विविधताएं बनाने के लिए किया जाता है। इन श्रेणीबद्ध कॉन्फ़िगरेशन के THM प्रदर्शन को निर्धारित करने और सर्वोत्तम प्रदर्शन करने वाले समान कॉन्फ़िगरेशन

के साथ तुलना करने के लिए संख्यात्मक सिमुलेशन किए जाते हैं। समग्र सर्वोत्तम कॉन्फिगरेशन निर्धारित करने के लिए प्रत्येक श्रेणी (अक्षीय, रेडियल और द्विदिशात्मक) से शीर्ष प्रदर्शन करने वाले कॉन्फिगरेशन की तुलना इनलेट वेग और अवशोषक लंबाई की एक श्रृंखला में की जाती है। यह देखा गया है कि *a-PI-SC*, *r-PC-SI* और *r-PD+a-SI* प्रत्येक श्रेणी का सबसे अच्छा प्रदर्शन करने वाला विन्यास है, यानी, अक्षीय, रेडियल और द्विदिशात्मक, 0.9 - 0.95 और छिद्र की सरंधता सीमा में आकार सीमा 2 - 4 मिमी. कुल मिलाकर, *r-PD+a-SI* कॉन्फिगरेशन दूसरे उच्चतम पीईसी और उच्चतम एफआई अनुपात के साथ सभी वर्गीकृत संरचनाओं के बीच बेहतर प्रदर्शन करता है। यह T_b में 8.96% की वृद्धि और F1 और ΔP में क्रमशः 22.7% और 4% की कमी दर्शाता है।

चूंकि VSR परिचालन के दौरान क्षणिक सौर प्रवाह का अनुभव करता है, गतिशील VSR प्रदर्शन का विश्लेषण करने के लिए एक क्षणिक थर्मो-मैकेनिकल मॉडल भी विकसित किया गया है। समय के साथ THM प्रदर्शन संकेतकों की भिन्नता की जांच वीएसआर के विभिन्न परिचालन चरणों के दौरान की जाती है, जिसमें स्टार्ट-अप, शटडाउन, दैनिक स्पष्ट आकाश संचालन और क्लाउड पासिंग शामिल हैं। साफ़-आसमान संचालन के दौरान वायु आउटलेट तापमान में लगभग 370 K का अंतर होता है, जिससे संभावित रूप से डाउनस्ट्रीम संचालन में व्यवधान उत्पन्न होता है। यह गतिशील नियंत्रण की आवश्यकता पर प्रकाश डालता है। THM प्रदर्शन पर विभिन्न स्टार्टअप और शट डाउन अवधि के प्रभाव की भी जांच की जाती है। छोटे स्टार्ट-अप और शट-डाउन अवधि के परिणामस्वरूप उच्च तापमान और F1 भिन्नताएं देखी गईं और इसके विपरीत। इसके अतिरिक्त, ठोस तापमान वितरण और विफलता सूचकांक पर क्लाउड ट्रांसमिसिविटी और ठोस मैट्रिक्स संरचना, जैसे छिद्र और छिद्र आकार, के प्रभाव का विश्लेषण किया जाता है। यह देखा गया कि शून्य संप्रेषणीयता वाले बादल सबसे खराब तापमान प्रवणता और उच्चतम F1 चोटियों का कारण बनते हैं।

इस कार्य के परिणाम VSR को बेहतर ढंग से डिजाइन करने और प्रदर्शन को बढ़ाने के लिए उचित मापदंडों का चयन करने के लिए मूल्यवान अंतर्दृष्टि प्रदान करते हैं, जिसके परिणामस्वरूप उच्च आउटपुट, कम पंपिंग शक्ति और उच्च यांत्रिक सुरक्षा होती है। जबकि विशिष्ट परिणाम मामले के आधार पर भिन्न हो सकते हैं, ये अवलोकन सामान्य डिज़ाइन विकल्पों के लिए एक मूल्यवान मार्गदर्शिका के रूप में काम करते हैं। समान विन्यास के लिए, 0.85 से अधिक छिद्र और 2 मिमी या उससे बड़े छिद्र आकार कुशल और सुरक्षित विन्यास के लिए उपयुक्त व्यापार-बंद प्रदान करते हैं। एक साथ अनुकूलन इस सीमा को 0.9-0.93 की सरंधता और 2-4 मिमी के छिद्र आकार तक परिष्कृत करता है। 0.9-0.95 की सरंधता सीमा के भीतर रैखिक उन्नयन और 2-4 मिमी की छिद्र आकार सीमा के साथ वर्गीकृत

विन्यास में, द्विदिशात्मक (r - $PD+a$ - SI) विन्यास सर्वोत्तम परिणाम देता है, इसके बाद अक्षीय (a - PI - SC) और रेडियल (r - PC - SI) विन्यास होता है ।

मुख्य शब्द: संकेंद्रित सौर ऊर्जा; वॉल्यूमेट्रिक सौर रिसेवर; छिद्रयुक्त मीडिया; थर्मो-मैकेनिकल मॉडलिंग; डीप न्यूरल नेटवर्क; बहुउद्देश्यीय अनुकूलन; जेनेटिक एल्गोरिथम, श्रेणीबद्ध संरचना

TABLE OF CONTENTS

CERTIFICATE	i
ACKNOWLEDGEMENTS	ii
ABSTRACT	iii
संक्षेप	vi
TABLE OF CONTENTS	x
LIST OF FIGURES	xiv
LIST OF TABLES	xix
NOMENCLATURE	xx
CHAPTER 1: INTRODUCTION	1
1.1 Background and motivation.....	1
1.2 Concentrated Solar Power (CSP).....	1
1.3 Volumetric Solar Receivers (VSR).....	2
1.4 Multiphysics modelling of a porous VSR.....	4
1.5 Organization of the thesis	6
CHAPTER 2: LITERATURE REVIEW AND RESEARCH OBJECTIVES	8
2.1 Studies related to porous VSRs.....	8
2.1.1 Experimental Studies	8
2.1.2 Numerical Studies	9
2.2 Optimization studies	14
2.2.1 Optimization using Genetic Algorithm (GA)	14
2.2.2 Artificial Neural Networks (ANN) assisted optimization studies	16
2.3 Functionally graded VSR.....	19
2.4 Dynamic operation of VSR.....	22
2.5 Research gaps from literature review	24
2.6 Objectives of present research	25
CHAPTER 3: DEVELOPMENT OF HYDRAULIC-THERMAL-MECHANICAL NUMERICAL MODEL FOR A POROUS VOLUMETRIC RECEIVER SUBJECTED TO CONCENTRATED SOLAR RADIATION	27
3.1 Introduction.....	27
3.2 Model description	28
3.2.1 Fluid Flow Model	30
3.2.2 Thermal Model.....	31
3.2.3 Radiative Heat Transfer Model.....	32
3.2.4 Thermo-Mechanical Stress Model.....	33
3.2.5 Material Properties	35
3.2.6 Boundary conditions	36
3.3 Numerical procedure and Grid Independence Study	38

3.4	Verification studies	39
3.5	Results and discussion	43
3.5.1	Effect of porosity	44
3.5.2	Effect of pore size	46
3.5.3	Effect of inlet velocity	48
3.5.4	Effect of receiver length.....	50
3.5.5	Effect of incident solar heat flux distribution	53
3.6	Chapter Summary and conclusion	57

CHAPTER 4: DEVELOPMENT OF A SURROGATE MODEL USING DEEP NEURAL NETWORKS FOR PERFORMANCE PREDICTION OF A POROUS VSR58

4.1	Introduction.....	58
4.2	Mathematical modelling of porous VSR	59
4.3	Deep Neural Network Model.....	59
4.3.1	Dataset generation for DNN	60
4.3.2	Normalization of data set	62
4.3.3	DNN model training	63
4.4	DNN performance Assessment.....	65
4.4.1	Comparison of training algorithms for DNN architecture with different number of neurons	65
4.4.2	Comparison of training algorithms for DNN architecture with different number of hidden layers.....	67
4.4.3	Comparison of results of DNN model with COMSOL simulations and individual parametric analysis	71
4.5	Chapter Summary and conclusion	73

CHAPTER 5: CONSTRAINED MULTI-OBJECTIVE OPTIMIZATION OF A POROUS VSR USING DNN MODEL75

5.1	Introduction.....	75
5.2	Numerical optimization	76
5.2.1	Multi-objective optimization (MOO) problem and algorithm.....	76
5.2.2	Multi-Criteria Decision Making with TOPSIS	79
5.3	Results.....	80
5.3.1	Comparison between DNN-assisted and conventional optimization.....	80
5.3.2	Simultaneous optimization of porosity and pore size	81
5.3.3	Simultaneous optimization of all input variables.....	86
5.4	Chapter Summary and conclusion	89

CHAPTER 6: THERMO-MECHANICAL PERFORMANCE ENHANCEMENT OF VSRs USING GRADED POROUS ABSORBERS.....91

6.1 Introduction.....91
6.2 Model description92
 6.2.1 Numerical model.....92
 6.2.2 Geometric structure.....92
 6.2.3 Geometric structure Solution Methodology.....95
 6.2.4 Receiver performance parameters.....95
6.3 Verification of the numerical model96
6.4 Results and discussion99
 6.4.1 Reference uniform configuration99
 6.4.2 Axial linear graded configurations.....100
 6.4.3 Radial linear graded configurations102
 6.4.4 Comparison of axial and radial graded variation104
 6.4.5 Bidirectional linear graded configurations.....106
 6.4.6 Selection of best configuration108
 6.4.7 Variation of THM parameters with inlet velocity.....109
 6.4.8 Variation of THM parameters with receiver length.....111
6.5 Chapter Summary and conclusion112

CHAPTER 7: DEVELOPMENT OF A TRANSIENT THERMO-MECHANICAL NUMERICAL MODEL FOR A POROUS VOLUMETRIC SOLAR RECEIVER113

7.1 Introduction.....113
7.2 Problem formulation114
 7.2.1 Fluid Flow Model114
 7.2.2 Thermal and Radiation Model115
 7.2.3 Mechanical Model115
 7.2.4 Closure parameters and material properties.....116
 7.2.5 Initial and boundary conditions117
7.3 Verification Studies120
7.4 Results and Discussion123
 7.4.1 Cold Startup123
 7.4.2 Clear sky daily operation126
 7.4.3 Cloud Passing.....128
 7.4.4 Shut down130
 7.4.5 Effect of porosity and pore size133
7.5 Chapter Summary and conclusion137

CHAPTER 8: CONCLUSIONS AND FUTURE SCOPE.....139

8.1	Final remarks and conclusions.....	139
8.2	Future scopes	143
	REFERENCES.....	145
	LIST OF PUBLICATIONS	160
	BRIEF BIODATA OF THE AUTHOR.....	161

LIST OF FIGURES

Fig. 1.1 Components and classification of Concentrating Solar Power (CSP) technology.....	2
Fig. 1.2 Classification of receiver technology	3
Fig. 1.3 Various types of porous absorbers employed in VSR (a) honeycomb, (b) ceramic foam and (c) wire mesh.....	4
Fig. 1.4 Solar-to-thermal energy conversion process in a porous VSR.....	5
Fig. 2.1 ANN Model (a) Artificial Neuron (b) ANN Architecture [97].....	17
Fig. 2.2 Linearly varied porous media (a) Manufactured via sintering (b) 3-D Reconstruction after X-ray tomography (reproduced from Du et al. [83] with permission from Springer Nature)	20
Fig. 3.1 (a) Schematic of a porous VSR and (b) Computational domain.....	29
Fig. 3.2 Flow chart for coupled thermo-mechanical numerical model.....	30
Fig. 3.3 Boundary conditions of the problem	38
Fig. 3.4 Comparison of results of Khashan et al. [146] with the present model (a) physical configuration and (b) LTNE contours at $Re = 100, Pe = 30, Da = 10 - 4, Bi = 200$	40
Fig. 3.5 Comparison of results of present study with Chen et al. [64] for (a) axial temperature distribution along the receiver's centreline, (b) solid radial temperature distribution at the receiver's front surface	41
Fig. 3.6 Physical domain of the problem in Jabbari et al. [147] for validation of thermo-mechanical coupling	42
Fig. 3.7 Comparison of results with Jabbari et al. [58] (a) temperature variation, (b) radial stress distribution and (c) hoop stress distribution.....	43
Fig. 3.8 Variation of thermal, hydraulic and mechanical performance indicators with porosity	44
Fig. 3.9 Effect of porosity on a) solid temperature, T_s , b) fluid temperature, T_f , c) Failure Index, FI	45
Fig. 3.10 Effect of pore size on thermal, hydrodynamic and mechanical performance indicators	47
Fig. 3.11 Effect of pore size on a) solid Temperature, T_s , b) Fluid Temperature, T_f , c) Failure Index, FI	48
Fig. 3.12 Variation of thermal, hydrodynamic and mechanical performance indicators with inlet velocity.....	49

Fig. 3.13 Effect of inlet velocity on a) solid temperature, T_s , b) fluid temperature, T_f , c) Failure Index, FI	50
Fig. 3.14 Effect of length of absorber on a) solid temperature, T_s , b) fluid temperature, T_f , c) Failure Index, FI	52
Fig. 3.15 Effect of receiver length on thermal, hydrodynamic and mechanical performance indicators.....	53
Fig. 3.16 Incident heat flux distributions with an equal amount of incident energy	54
Fig. 3.17 Effect of incident solar heat flux distribution on a) solid temperature, T_s , b) fluid temperature, T_f , c) Failure Index, FI	55
Fig. 3.18 Air outlet temperature, $T_{b, out}$, pressure drop, ΔP , and Failure Index, FI , for various incident flux distributions	56
Fig. 4.1 Flow chart showing ANN architecture and model development	60
Fig. 4.2 Bar chart showing the distribution of input data set over the selected range (a) Porosity, (b) Pore size, (c) Inlet velocity and (d) Absorber length	61
Fig. 4.3 Bar chart showing the distribution of output data set over the selected range (a) air outlet temperature, (b) pressure drop, and (c) Failure Index	62
Fig. 4.4 Comparison of various training algorithms for ANN model with different number of neurons and a single hidden layer: (a) MAPE in air outlet temperature prediction, (b) MAPE in pressure drop prediction, (c) number of epochs required by various training algorithms and (d) training time of algorithms.....	66
Fig. 4.5 Comparison of various training algorithms for ANN model with different number of hidden layers and 20 neurons per layer: (a) MAPE in air outlet temperature prediction, (b) MAPE in pressure drop prediction, (c) number of epochs required by various training algorithms and (d) training time of algorithms	68
Fig. 4.6 Relative error for test set with (a) different number of layers and (b) different number of neurons per layer	69
Fig. 4.7 Deep Neural Network architecture for performance prediction of porous solar absorber	70
Fig. 4.8 DNN Training with LM Backpropagation (a) loss function v/s epochs, (b) regression plot for training set, (c) regression plot for validation set and (d) regression plot for test set.	71
Fig. 4.9 Comparison of results of the DNN model and COMSOL simulation: Performance parameters, $T_{b, out}$, ΔP and FI , v/s (a) ϕ , (b) dp , (c) U_{in} and (d) L . The default values of ϕ , dp , U_{in} and L are fixed at 0.8, 2.5 mm, 1 m/s and 0.05 m, respectively.	72

Fig. 4.10 Comparison of results of the DNN model and COMSOL simulation: Relative errors in Performance parameters, Tb, out , ΔP and FI , v/s (a) ϕ , (b) dp , (c) U_{in} and (d) L .	73
Fig. 5.1 Flow chart representing Genetic Algorithm for Multi-Objective Optimization using DNN model	78
Fig. 5.2 Steps in TOPSIS method for selection of best alternative from Pareto front	80
Fig. 5.3 Optimized Pareto front of objective functions and corresponding optimum variables for different velocities at $L = 0.05\text{ m}$. The Pareto fronts for Tb, out v/s ΔP are shown in (a), (c) and (e) and corresponding optimum porosities and pore sizes are shown in (b), (d) and (f).	83
Fig. 5.4 Optimized Pareto front of objective functions and corresponding optimum variables for different absorber lengths at $U_{in} = 1\text{ m/s}$. The Pareto fronts for Tb, out v/s ΔP are shown in (a), (c) and (e) and corresponding optimum porosities and pore sizes are shown in (b), (d) and (f).	85
Fig. 5.5 Pareto front of Tb, out v/s ΔP for simultaneous optimization	87
Fig. 5.6 Plots for simultaneous optimization: Pareto optimal values of decision variables- Porosity (a), Pore size (b), Inlet velocity (c) and Absorber length (d) in terms of corresponding optimized performance parameters (Tb, out , ΔP and FI)	88
Fig. 6.1 Geometric structure of graded VSR: (a) increasing axial variation ($a-PI$ or $a-SI$), (b) decreasing axial variation ($a-PD$ or $a-SD$), (c) increasing radial variation ($r-PI$ or $r-SI$) and (d) decreasing radial variation ($r-PD$ or $r-SD$). Variable var denotes porosity or pore size.	94
Fig. 6.2 Schematic of the physical domain of the problem in Chen et al. [64]	97
Fig. 6.3 Comparison of results of this study with Chen et al. [64] for (a) axial temperature distribution along receiver's centreline, (b) radial temperature distribution at the receiver front	98
Fig. 6.4 Selection of the reference uniform configuration: (a) THM performance parameters (b) PEC and FI Ratio, for various uniform configurations. The pore size is kept constant at the average value of 3 mm.	100
Fig. 6.5 THM performance parameters for axial linear graded configurations (a) Air outlet temperature, Tb, out , (b) Pressure drop, ΔP and (c) Failure Index, FI	101
Fig. 6.6 Comparison of various axial linear graded configurations in terms of (a) PEC and (b) FI Ratio	102
Fig. 6.7 THM performance parameters for radial linear graded configurations (a) Air outlet temperature, Tb, out , (b) Pressure drop, ΔP and (c) Failure Index, FI	103

Fig. 6.8 Comparison of various radial linear graded configurations in terms of (a) <i>PEC</i> and (b) <i>FI Ratio</i>	104
Fig. 6.9 Comparison of Radial and Axial graded Configurations in terms of (a) Air outlet temperature, <i>T_{b, out}</i> , (b) Pressure Drop, ΔP and (c) Failure Index, <i>FI</i>	105
Fig. 6.10 Comparison of Radial and Axial graded configurations in terms of (a) <i>PEC</i> and (b) <i>FI Ratio</i>	106
Fig. 6.11 TMH performance parameters for bidirectional graded configurations: (a) Air outlet temperature, <i>T_{b, out}</i> , (b) Pressure Drop, ΔP and (c) Failure Index, <i>FI</i>	107
Fig. 6.12 Comparison of various bidirectional linear graded configurations in terms of (a) <i>PEC</i> and (b) <i>FI Ratio</i>	107
Fig. 6.13 THM characteristics of best configurations of each graded category: (a) velocity, <i>U</i> (b) solid temperature, <i>T_s</i> (c) fluid temperature, <i>T_f</i> and (d) Failure Index, <i>FI</i>	109
Fig. 6.14 THM characteristics of best graded configurations at various velocities (a) Air outlet temperature, <i>T_{b, out}</i> , (b) Pressure Drop, ΔP and (c) Failure Index, <i>FI</i>	110
Fig. 6.15 THM characteristics of best graded configurations at various receiver lengths (a) air outlet temperature, <i>T_{b, out}</i> , (b) Pressure Drop, ΔP and (c) Failure Index, <i>FI</i>	111
Fig. 7.1 Schematic of the physical domain.....	114
Fig. 7.2 Incident solar flux distribution during a CSP operation: (a) cold start-up, (b) cloud-pass, (c) clear sky day operation, and (d) shut-down.....	119
Fig. 7.3 Schematic of the physical domain in Ren et al. [61].....	120
Fig. 7.4 Comparison of fluid and solid temperature distributions obtained in the present study and Ren et al. [61] when (a) sudden transient flux variation from 1 MW/m ² to 0 and (b) frequent solar changing with a cooling interval time of 50 s	121
Fig. 7.5 Schematic of physical domain in Awaji and Sivakumar [166]	122
Fig. 7.6 Verification of transient thermo-mechanical coupling by reproducing results of Awaji and Sivakumar [166] (a) variation of non-dimensional temperature, (b) variation of non-dimensional hoop stress and (c) variation of non-dimensional hoop stress distribution with Biot Number	123
Fig. 7.7 Transient response of receiver during cold start-up: (a) incident solar flux variation, (b) solid temperature, (c) fluid temperature	124
Fig. 7.8 Air outlet temperature and pressure drop during cold startup.....	125
Fig. 7.9 (a) Solid temperature variation at point C (b) variation of maximum Failure Index, <i>FI</i> for different start-up durations	126

Fig. 7.10 Transient response of receiver during clear sky operation: (a) incident solar flux variation, (b) solid temperature, (c) fluid temperature.....	127
Fig. 7.11 Variation of (a) pressure drop and air outlet temperature, (b) Failure Index, FI during clear sky operation	127
Fig. 7.12 Transient response of receiver during cloud passing: (a) incident solar flux variation, (b) solid temperature, (c) fluid temperature	129
Fig. 7.13 Pressure drop and air outlet temperature during cloud passing.....	129
Fig. 7.14 (a) Solid Temperature variation at point C (b) Variation of maximum Failure Index, FI for different cloud emissivities.....	130
Fig. 7.15 Transient response of receiver during shut down: (a) Incident solar flux distribution, (b) Solid Temperature, (c) Fluid Temperature.....	131
Fig. 7.16 Air Outlet Temperature and Pressure drop during shut down period	132
Fig. 7.17 (a) Solid temperature variation at Location C (b) Variation of maximum Failure Index, FI for different shut-down periods.....	133
Fig. 7.18 Effect of porosity on solid temperature distribution at $z=L/2$ (Point C) and maximum Failure Index, FI, respectively, for cold startup (a) and (b), cloud pass (c) and (d), shut down (e) and (f)	135
Fig. 7.19 Effect of porosity on solid temperature distribution at $z=L/2$ (Point C) and maximum Failure Index, FI, respectively, for cold startup (a) and (b), cloud pass (c) and (d), shut down (e) and (f)	137

LIST OF TABLES

Table 3.1 Mechanical and Thermophysical properties of SiC	36
Table 3.2 Boundary conditions for governing equations	37
Table 3.3 Grid independency test: Variation of air outlet temperature, pressure drop, and failure index with the number of elements	39
Table 3.4 Comparison of results of present study with Chen et al. [64].....	41
Table 4.1. Input variables and their ranges used for DNN data generation	61
Table 4.2 Training Algorithms.....	64
Table 5.1. Objectives and Constraints for Multi-objective Optimization.....	77
Table 5.2. Best performance values with TOPSIS for different velocities	84
Table 5.3. Best performance values with TOPSIS for different absorber lengths	86
Table 5.4. Best performance values for simultaneous optimization of all variables with TOPSIS	89
Table 6.1 Axially and radially graded absorber configurations	94
Table 6.2 Bidirectional graded absorber configurations	95
Table 6.3 Comparison of results of this study with Chen et al. [64]: Maximum percentage deviation in centerline solid and fluid temperature distributions and front solid temperature distribution	99
Table 6.4 Comparison of best performing configurations in various graded categories	108
Table 7.1 Closing parameters and effective properties for governing equations.....	116

NOMENCLATURE

C_F	Inertial coefficient
C_p	Specific heat (J/kg K)
d_p	Pore size (m)
E	Youngs Modulus (GN/m ²)
G	Incident irradiation (W/m ²)
h_v	Volumetric Heat Transfer Coefficient (W/m ³ K)
Nu_v	Volumetric Nusselt Number
k	Thermal conductivity (W/mK)
K	Permeability (m ²)
L	Length (m)
p	pressure (Pa)
q	incident solar radiation (W/m ²)
q_o	Steady-state incident solar radiation (W/m ²)
r	Radial Coordinates (m)
κ_{abs}	Absorption coefficient (1/m)
S_{rad}	Radiative source term (W/m ³)
s_{sca}	Scattering coefficient (1/m)
T	Temperature (K)
U	Velocity (m/s)
u	Pore Velocity (m/s)
z	Axial Coordinate (m)

GREEK SYMBOLS

α_t	Linear coefficient of thermal expansion (1/K)
β	Extinction coefficient (1/m)
δ	Kronecker delta
ϵ	emissivity
ε	Strain
μ	dynamic viscosity (Pa s)
ϕ	porosity
ρ	density (kg/m ³)

σ	Stefan-Boltzmann constant (W/m ² K ⁴)
τ	Stress (MN/m ²)
ν	Poisson's Ratio

SUBSCRIPTS

<i>amb</i>	Ambient
<i>b</i>	Mean bulk
<i>c</i>	Collimated
<i>d</i>	Diffuse
<i>D</i>	Decreasing
<i>e</i>	Effective
<i>f</i>	Fluid
<i>I</i>	Increasing
<i>in</i>	Inlet
<i>i, j, k</i>	Tensor indices
<i>out</i>	Outlet
<i>p</i>	Principal
<i>rad</i>	Radiation
<i>s</i>	Solid
<i>sm</i>	Solid matrix

SUPERSCRIPTS

\sim	Relative Properties
<i>M</i>	Mechanical
<i>T</i>	Thermal

ABBREVIATIONS

<i>a</i>	Axial graded
ANN	Artificial Neural Network
CFD	Computational Fluid Dynamics
CSP	Concentrated Solar Power
DNN	Deep Neural Network

FEM	Finite Element Method
<i>FI</i>	Failure Index
GA	Genetic Algorithm
HEM	Homogeneous Equivalent Method
HTF	Heat Transfer Fluid
LTE	Local Thermal Equilibrium
LTNE	Local Thermal Non-Equilibrium
MAPE	Mean Absolute Percentage Error
MCRT	Monte Carlo Ray Tracing
MCDM	Multi-Criteria Decision Making
MOO	Multi-Objective Optimization
<i>PC</i>	Porosity Constant
<i>PD</i>	Porosity Decreasing
<i>PI</i>	Porosity Increasing
<i>SC</i>	Pore Size Constant
<i>SD</i>	Pore Size Decreasing
<i>SI</i>	Pore Size Increasing
SiC	Silicon Carbide
<i>PEC</i>	Performance Evaluation Criterion
<i>r</i>	Radial graded
VSR	Volumetric Solar receiver
THM	Thermal-Hydraulic-Mechanical
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
<i>U</i>	Uniform
VHTC	Volumetric Heat Transfer Coefficient