

**INVESTIGATION ON DIRECT STEAM GENERATION
IN PARABOLIC TROUGH SOLAR COLLECTOR**

Ram Kumar Pal



**DEPARTMENT OF ENERGY SCIENCE AND ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

July 2023

© Indian Institute of Technology Delhi (IITD), New Delhi, 2023

**INVESTIGATION ON DIRECT STEAM GENERATION
IN PARABOLIC TROUGH SOLAR COLLECTOR**

by

Ram Kumar Pal

Department of Energy Science and Engineering

Submitted

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



INDIAN INSTITUTE OF TECHNOLOGY DELHI

July 2023

Certificate

This is to certify that this thesis entitled "**Investigation on Direct Steam Generation in Parabolic Trough Solar Collector**" being submitted by **Mr. Ram Kumar Pal** (Entry No.- 2017ESZ8543) to the 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**, India.

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.

Dr. K. Ravi Kumar

Associate Professor

Department of Energy Science and Engineering

Indian Institute of Technology Delhi

New Delhi, India

Acknowledgments

I am immensely pleased to express my gratitude to those who supported me during this doctoral study. First and foremost, I would like to express my whole-hearted gratitude, deep regards, and sincere thanks to my Ph.D. advisor Prof. K. Ravi Kumar, for his invaluable, thoughtful guidance throughout my Ph.D. study at the Department of Energy Science and Engineering, Indian Institute of Technology Delhi, New Delhi, India. His encouragement and support have been a constant source of inspiration ever since I entered this exciting field of research.

I sincerely thank my research committee members, Prof. Tara Chandra Kandpal, Prof. M. R. Ravi, and Prof. Dibakar Rakshit, for their invaluable advice during the various evaluation stages of my research work. I am also extremely grateful to the Head of the Department of Energy Science and Engineering for providing facilities and extending every possible support.

I would like to acknowledge the Science and Engineering Research Board (SERB), Ministry of Science and Technology, Government of India, New Delhi, for providing financial support (Project No.: ECR/2017/000164) for this research work.

I would like to express my sincere regards and thanks to Mr. Dhanne Singh, Dr. Anish Malan, Dr. Tarun Kumar Aseri, and all my labmates, especially to Sumeet Kumar Dubey for their suggestions, constant encouragement, and generous help at all stages of my research work. I would also like to thank the institute administrators and technical/official staff for their active support throughout my doctoral program.

I wish to express my gratitude to my parents, brother, and sister for providing support and blessings that have helped to complete my research work. I am deeply grateful to my wife Mrs. Preeti Pal for her unwavering support, love, and understanding throughout the entire process of this research program. Her encouragement and belief in my abilities have been a constant source of strength, and her sacrifices and patience have enabled me to focus on my research and academic pursuits. I would also like to extend my heartfelt appreciation to my dear daughter Prisha. Her boundless joy, innocence, and love have been a constant source of inspiration and motivation for me.

(Ram Kumar Pal)

Abstract

A parabolic trough solar collector (PTSC) used for direct steam generation (DSG) has the potential to bring down the levelized cost of electricity (LCOE) by performance improvement and reduction in capital cost. However, the application of DSG in PTSC for solar thermal power generation is in the nascent stage and needs improvement in the components of PTSC and process control mechanisms. The DSG process comprises preheating, evaporation, and superheating of steam in the solar collectors. The DSG using PTSC is facing thermal-hydraulic instability and controllability issues in its commercialization. The modeling and simulation of DSG are challenging because of the complexities associated with the boiling phase change in the evaporation section. In view of this, an attempt has been made for the thermal-hydraulic investigation of DSG in PTSC. Further, the structural stability analysis of the absorber tube of PTSC has been performed for DSG.

The Eulerian two-fluid modeling approach, coupled with the mass transfer and critical heat flux boiling models, has been used to model the DSG process in a three-dimensional (3-D) computational domain. Interfacial interactions, such as mass, momentum, and energy exchanges between liquid and vapor, have been modeled using appropriate empirical correlations.

The thermal-hydraulic study has been performed for DSG in a 12 m long single module of PTSC. The analysis has been performed for both uniform and non-uniform concentrating solar flux profiles around the absorber surface at solar noontime with direct normal irradiance (DNI) of 750 W/m^2 . Further, the effect of inlet mass flow rates (0.3 kg/s to 0.6 kg/s) and operating pressures (30 bar to 100 bar) have been investigated. It has been observed that the vapor volume fraction at the outlet varies between 0.3 to 0.6, and the flow pattern is stratified flow under the subjected boundary conditions. The absorber's outer surface temperature varies in the range of 517 K to

639 K under uniform heat flux conditions and 511 K to 603 K under non-uniform heat flux conditions. The maximum circumferential temperature difference in the absorber is 77 K under uniform heat flux conditions and 16 K under non-uniform heat flux conditions. The circumferential temperature difference and pressure loss decrease with an increase in the operating pressure.

The characteristics of the concentrating solar flux profile on the absorber tube continuously vary from morning to evening because of the apparent motion of the sun and tracking of the solar collector. It results in the shifting of a non-uniform heat flux profile on the absorber surface that induces a high-temperature gradient in the absorber. The study has been performed to investigate the impact of concentrating solar flux profiles corresponding to various solar times of the day. It has been observed that absorber wall temperature varies between 550 K to 638 K from morning to evening for a DNI of 750 W/m^2 . If the DNI increases to 1000 W/m^2 , absorber wall temperature varies between 550 K to 656 K. The maximum circumferential temperature differences at DNI of 750 W/m^2 are 60 K and 51 K, respectively, at 60 bar and 100 bar operating pressures. Similarly, when DNI increases to 1000 W/m^2 , the maximum circumferential temperature differences are 79 K and 69 K, respectively, at 60 bar and 100 bar operating pressures.

The modeling of all three zones of PTSC row privileges identifying the critical process conditions leading to thermal-hydraulic instabilities in the DSG solar field and is beneficial for the engineering design of components forming the DSG solar field. In view of this, a study has been performed for thermal-hydraulic investigation of DSG in a 500 m long row of PTSC. It has been observed that the maximum absorber temperature is reduced by 27% at 60 bar and 20% at 100 bar operating pressure when the inlet mass flow rate increases from 0.4 kg/s to 0.6 kg/s. Similarly, the maximum circumferential temperature difference reduces by 12% and 14%, respectively.

Moreover, the fluid temperature, steam quality, absorber temperature distributions, fluid velocity, and pressure loss have been summarized.

The conventional absorber tubes (inner surface is smooth) suffer from thermal instability due to a high non-uniform temperature gradient. The absorber's configuration affects the capability of collection and extraction of heat from the receiver. The absorber's thermal performance could be improved by introducing circumferential grooves etched at the inner surface. In view of this, a thermal-hydraulic investigation of a grooved absorber has been performed and compared with the conventional absorber. It has been observed that the maximum absorber temperature is reduced by up to 6 K with the grooved absorber. Simultaneously, the circumferential temperature difference is reduced by 2 to 3 K. Further, the pressure loss in the grooved absorber is increased by up to 8 times as compared to the conventional smooth absorber.

The absorber tube is a key component of a PTSC, and the bending of the absorber has an important role in receiver failures. The detailed survey of existing commercial PTSC power plants reveals that 55% of failures happened due to the rupture of glass envelope and 29% due to the loss in annulus vacuum. In view of this, coupled thermal-hydraulic and structural stability analyses have been performed to understand the thermo-structural performance of absorber tubes. The deflection in the absorber is maximum in the superheating section, followed by preheating section and evaporation section. The maximum deflection in the absorber at 60 bar and 100 bar operating pressures are 17.1 mm and 16.3 mm, respectively, which are at an inlet mass flow rate of 0.4 kg/s. Simultaneously, there may be a thermal expansion of up to 23.22 mm and 25.37 mm at 60 bar and 100 bar operating pressure, respectively.

In summary, the study presents a detailed thermal-hydraulic investigation of DSG in parabolic trough solar collectors using the Eulerian two-fluid modeling approach because it offers more

accurate results as compared to the homogeneous equilibrium modeling approach. The thermal-hydraulic impacts of several influencing parameters, such as mass flow rate, operating pressure, DNI, absorber configuration, and concentrating solar flux profiles, have been investigated. The deep insight observations of the thermal-hydraulic behavior of the DSG process are presented under realistic operating conditions and are useful for the configuration of the DSG solar field for optimum performance. Further, the obtained results could be employed for the engineering design of the receiver of PTSC and the development of the DSG technology.

सारांश

प्रत्यक्ष भाप उत्पादन (डीएसजी) के लिए उपयोग किए जाने वाले पैराबोलिक ट्रफ सोलर कलेक्टर (पीटीएससी) के प्रदर्शन में सुधार और पूंजीगत लागत में कमी के माध्यमों में विद्युत् उत्पादन की लागत को कम करने की क्षमता है। तथापि, सौर तापीय विद्युत् उत्पादन के लिए पीटीएससी में डीएसजी का अनुप्रयोग प्रारंभिक चरण में है और पीटीएससी के घटकों व प्रक्रिया नियंत्रण तंत्रों में सुधार की आवश्यकता है। डीएसजी प्रक्रिया में सौर संग्राहकों में भाप का पूर्वतापन, वाष्पीकरण और अतितापन शामिल है। पीटीएससी के द्वारा डीएसजी के व्यावसायीकरण में ऊष्मीय व द्रवीय अस्थिरता और नियंत्रणीयता के जैसे मुद्दों का सामना करना पड़ रहा है। वाष्पीकरण अनुभाग में उबलते चरण परिवर्तन से जुड़ी जटिलताओं के कारण डीएसजी की मॉडलिंग और सिमुलेशन चुनौतीपूर्ण है। इसे देखते हुए पीटीएससी में डीएसजी की ऊष्मीय व द्रवीय जांच का प्रयास किया गया है। इसके अलावा, डीएसजी के लिए पीटीएससी के अवशोषक पाइप की संरचनात्मक स्थिरता का विश्लेषण किया गया है।

द्रव्यमान स्थानांतरण और समीक्षात्मक ऊष्मीय स्थानांतरण प्रतिरूप के साथ यूलेरियन टू-फ्लूइड मॉडलिंग दृष्टिकोण का उपयोग त्रिआयामी (3-डी) अभिकलनी अनुक्षेत्र में डीएसजी प्रक्रिया को मॉडल करने के लिए किया गया है। तरल व वाष्प के बीच द्रव्यमान, संवेग और ऊर्जा विनिमय जैसी अंतरापृष्ठीय अन्योन्यक्रिया को उचित अनुभवजन्य सहसंबंधों का उपयोग करके प्रतिरूपित किया गया है।

पीटीएससी के एक 12 मीटर लंबी इकाई में डीएसजी के लिए ऊष्मीय व द्रवीय अध्ययन किया गया है। यह विश्लेषण दोपहर के लिए 750 W/m^2 के प्रत्यक्ष सामान्य विकिरण (डीएनआई) के साथ अवशोषक पाइप की बाहरी सतह के चारों ओर समान और असमान केंद्रित सौर प्लक्स प्रोफाइल के लिए किया गया है। इसके अलावा, अन्तर्गम द्रव्यमान प्रवाह (0.3 किलोग्राम/सेकंड से 0.6 किलोग्राम/सेकंड) और परिचालन दाब (30 bar से 100 bar) के प्रभाव की जांच की गई है। यह देखा गया है कि पाइप के निर्गम पर वाष्प का मात्रांश 0.3

से 0.6 के बीच होता है, और प्रवाह का स्वरूप स्तरीकृत होता है। अवशोषक पाइप की बाहरी सतह का तापमान समान ऊष्मा प्रवाह की स्थितियों के अंतर्गत 517 K से 639 K के बीच और असमान ऊष्मा प्रवाह स्थितियों के अंतर्गत 511 K से 603 K के बीच होता है। अवशोषक पाइप में अधिकतम परिधीय तापांतर समान ऊष्मा प्रवाह स्थितियों के अंतर्गत 77 K है और असमान ऊष्मा प्रवाह के अंतर्गत 16 K है। परिचालन दाब में वृद्धि के साथ तापांतर और दाब हानि कम हो जाती है।

अवशोषक पाइप के बाहरी सतह पर केंद्रित सौर फ्लक्स प्रोफाइल की विशेषताएं सूर्य की स्पष्ट गति और सौर संग्राहक के मार्गन के कारण सुबह से शाम तक लगातार बदलती रहती हैं। इसके परिणामस्वरूप अवशोषक पाइप के बाहरी सतह पर असमान ऊष्मा फ्लक्स प्रोफाइल का स्थानांतरण होता है जो अवशोषक पाइप में उच्च तापीय प्रवणता को प्रेरित करता है। दिन के विभिन्न सौर समयों के अनुरूप सौर फ्लक्स प्रोफाइल के प्रभाव की जांच करने के लिए एक अध्ययन किया गया है। यह देखा गया है कि अवशोषक पाइप का तापमान 750 W/m^2 डीएनआई के लिए सुबह से शाम तक 550 K से 638 K की सीमा में होता है। यदि डीएनआई 1000 W/m^2 तक बढ़ जाता है, तो अवशोषक पाइप का तापमान 550 K से 656 K की सीमा में होता है। 750 W/m^2 डीएनआई पर अधिकतम परिधीय तापांतर 60 bar और 100 bar परिचालन दाब पर क्रमशः 60 K और 51 K है। इसी तरह, जब डीएनआई 1000 W/m^2 तक बढ़ जाता है, तो अधिकतम परिधीय तापांतर 60 bar और 100 bar परिचालन दाब पर क्रमशः 79 K और 69 K होता है।

सौर क्षेत्र में पीटीएससी कतार के सभी तीन भागों की मॉडलिंग डीएसजी में ऊष्मीय व द्रवीय अस्थिरता के महत्वपूर्ण कारकों की पहचान कराती है और सौर क्षेत्र बनाने वाले घटकों की अभियांत्रिकी अभिकल्पना के लिए लाभदायक है। इसे देखते हुए पीटीएससी की 500 मीटर लंबी कतार में डीएसजी की ऊष्मीय व द्रवीय जांच की गयी है। यह देखा गया है कि जब अन्तर्गम द्रव्यमान प्रवाह 0.4 किलोग्राम/सेकंड से बढ़कर 0.6 किलोग्राम/सेकंड हो जाता है तो अवशोषक पाइप का अधिकतम तापमान 60 bar और 100 bar परिचालन

दाब पर क्रमशः 27% और 20% कम हो जाता है। इसी तरह, अधिकतम परिधीय तापांतर क्रमशः 12% और 14% कम हो जाता है। इसके अलावा, द्रव तापमान, भाप की गुणवत्ता, अवशोषक पाइप पर तापमान वितरण, द्रव वेग और दाब हानि को संक्षेप में प्रस्तुत किया गया है।

पारंपरिक अवशोषक पाइप की आंतरिक सतह चिकनी होती है और वह उच्च असमान तापीय प्रवणता के कारण ऊष्मीय अस्थिरता से पीड़ित है। अवशोषक पाइप का विन्यास रिसीवर से ऊष्मा के संग्रहण और निष्कर्षण की क्षमता को प्रभावित करता है। अवशोषक पाइप की आंतरिक सतह पर परिधीय खांचे उकेरकर उसके ऊष्मीय प्रदर्शन में सुधार किया जा सकता है। इसे देखते हुए, एक आंतरिक सतह पर परिधीय खांचे उकेरे हुए अवशोषक पाइप की ऊष्मीय एवं द्रवीय जांच की गई है और इसकी पारंपरिक अवशोषक पाइप के साथ तुलना की गई है। यह देखा गया है कि अवशोषक पाइप की आंतरिक सतह पर परिधीय खांचे उकेरने पर उसका अधिकतम तापमान पारंपरिक अवशोषक पाइप के सापेक्ष 6 K तक कम हो जाता है। इसके साथ ही, परिधीय तापांतर 2 K से 3 K तक कम हो जाता है। इसके अलावा, पारंपरिक अवशोषक पाइप की तुलना में दाब हानि 8 गुना तक बढ़ जाती है।

अवशोषक पाइप पीटीएससी का एक प्रमुख घटक है। इसका नीचे की तरफ झुकाव रिसीवर की विफलताओं का एक प्रमुख कारण है। मौजूदा वाणिज्यिक पीटीएससी बिजली संयंत्रों के विस्तृत सर्वेक्षण से पता चलता है कि 55% विफलताएं कांच के आवरण के टूटने के कारण हुईं और 29% वलय निर्वात में नुकसान के कारण हुईं। इसे देखते हुए, अवशोषक पाइप के ऊष्मीय एवं संरचनात्मक प्रदर्शन को समझने के लिए युग्मित ऊष्मीय व द्रवीय और संरचनात्मक स्थिरता का विश्लेषण किया गया है। अवशोषक पाइप में विक्षेपण अतितापन अनुभाग में अधिकतम होता है, इसके बाद पूर्वतापन अनुभाग और वाष्पीकरण अनुभाग में होता है। 60 bar और 100 bar परिचालन दाब पर अवशोषक पाइप में अधिकतम विक्षेपण क्रमशः 17.1 मिमी और

16.3 मिमी है, जो 0.4 किलोग्राम/सेकंड के अन्तर्गम द्रव्यमान प्रवाह दर पर हैं। इसके साथ ही, 60 bar और 100 bar परिचालन दाब पर क्रमशः 23.22 मिमी और 25.37 मिमी तक का ऊष्मीय विस्तार हो सकता है।

सारांशतः यह अध्ययन यूलेरियन टू-फ्लूइड मॉडलिंग दृष्टिकोण का उपयोग करके पैराबोलिक ट्रफ सोलर कलेक्टर में डीएसजी की एक विस्तृत ऊष्मीय व द्रवीय जांच प्रस्तुत करता है क्योंकि यह सजातीय संतुलन मॉडलिंग दृष्टिकोण की तुलना में अधिक सटीक परिणाम प्रदान करता है। द्रव्यमान प्रवाह दर, परिचालन दाब, डीएनआई, अवशोषक पाइप में विन्यास और सौर प्रवाह प्रोफाइल जैसे कई मापदंडों की अवशोषक पाइप के ऊष्मीय व द्रवीय व्यवहार पर प्रभाव की जांच की गई है। डीएसजी प्रक्रिया का यथार्थवादी परिचालन स्थितियों के अंतर्गत ऊष्मीय व द्रवीय व्यवहार का गहरी अंतर्दृष्टि से अवलोकन प्रस्तुत किया गया है। इसके अलावा, प्राप्त परिणामों को पीटीएससी के रिसेवर की अभियांत्रिकी अभिकल्पना और डीएसजी तकनीक के विकास के लिए नियोजित किया जा सकता है।

Contents

	Page No.
Certificate	i
Acknowledgments	ii
Abstract	iii
Contents	xi
List of Figures	xv
List of Tables	xxiii
Nomenclature	xxv
Chapter 1 Introduction	1
1.1 Relevance and Justification of the Study	1
1.2 Direct Steam Generation in PTSC	6
1.2.1 Once-Through Mode of DSG Process	8
1.2.2 Recirculation Mode of DSG Process	9
1.2.3 Injection Mode of DSG Process	9
1.3 Concluding Remarks	10
Chapter 2 Literature Review	12
2.1. Historical Development of DSG in Parabolic Trough Solar Collector	12
2.2. Thermo-Hydrodynamics of Direct Steam Generation Process	24
2.2.1. Flow Pattern Maps in the DSG Process	26
2.2.2. Thermal-Hydraulic Modeling of DSG	31
2.3. Effect of Concentrated Solar Flux on Thermal Performance of DSG in PTSC	46
2.4. Thermal Performance of Grooved Absorber in DSG Process	48
2.5. Structural Stability of the Receiver for DSG in PTSC	49
2.6. Research Gaps	51
2.7. Objectives of the Study	52

2.8. Outline of the Thesis	53
2.9. Concluding Remarks	57
Chapter 3 Two-Fluid Modeling of Direct Steam Generation in Absorber Tube with Uniform and Non-Uniform Concentrating Solar Flux	58
3.1. Introduction	58
3.2. Mathematical Modeling	59
3.2.1. Volume Fraction Equation	60
3.2.2. Conservation Equations	60
3.2.3. Interfacial Forces in Momentum Equation	62
3.2.4. Turbulence Modeling	63
3.2.5. Modeling of Mass Transfer	64
3.2.6. Modeling of Heat Transfer	66
3.3. Computational Domain and Boundary Conditions	68
3.4. Numerical Methodology	73
3.5. Model Validation	73
3.6. Results and Discussion	75
3.6.1. DSG in PTSC with Uniform Heat Flux Applied on the Absorber Surface	76
3.6.2. DSG in PTSC with Non-Uniform Heat Flux Applied on the Absorber Surface	93
3.7. Concluding Remarks	103
Chapter 4 Impact of Position of Concentrated Solar Flux Profile on the Absorber Surface for Direct Steam Generation in the Parabolic Trough Solar Collector	106
4.1. Introduction	106
4.2. Modeling of Direct Steam Generation	107
4.3. Computational Domain and Boundary Conditions	108
4.4. Numerical Simulation Procedure	111
4.5. Results and Discussion	111
4.6. Concluding Remarks	129

Chapter 5	Thermo-Hydraulic Analysis of Direct Steam Generation in a 500 m Long Row of Parabolic Trough Solar Collector using Eulerian Two-Fluid Modeling Approach	131
5.1	Introduction	131
5.2	Description of the DISS Experimental Test Facility	133
5.3	Mathematical Modeling Approach	134
5.4	Numerical Techniques and Model Validation	135
5.4.1	Boundary Conditions	135
5.4.2	Numerical Methodology	137
5.4.3	Numerical Model Validation with DISS Experimental Data	138
5.5	Results and Discussion	141
5.6	Concluding Remarks	158
Chapter 6	Impact of Circumferential Grooves on Thermal Performance of the Absorber of PTSC for Direct Steam Generation	160
6.1	Introduction	160
6.2	Mathematical Modeling of DSG in a Grooved Absorber	163
6.3	Computational Domain and Boundary Conditions	163
6.4	Results and Discussion	167
6.5	Concluding Remarks	177
Chapter 7	Coupled Thermo-Structural Analysis of Absorber Tube of Parabolic Trough Solar Collector for Direct Steam Generation	178
7.1	Introduction	178
7.2	Mathematical Modeling	180
7.2.1	Governing Equations for Thermo-Hydraulic Analysis	180
7.2.2	Governing Equations for Structural Analysis of Absorber Tube	183
7.3	Numerical Methodology	184
7.3.1	Computational Domain and Boundary Conditions	184
7.3.2	Simulation Procedure	188
7.3.3	Numerical Model Validation	190
7.4	Results and Discussion	192

7.5 Concluding Remarks	207
Chapter 8 Conclusions and Recommendations for Future Work	209
References	216
List of Publications	235
About the Author	237

List of Figures

Figure No.	Title of Figure	Page No.
Figure 1.1	Schematic of concentrating solar thermal energy system and its applications	2
Figure 1.2	Comparison of benefits of CSP technologies with other renewable energy technologies for electricity generation	4
Figure 1.3	Commercially available CSP technologies: (a) parabolic trough solar collector, (b) linear Fresnel reflector, (c) central tower receiver, and (d) parabolic dish collector	5
Figure 1.4	Schematic of (a) parabolic trough solar collector field and (b) zoom-in view of its components	6
Figure 1.5	Comparison between thermal oil-based solar power plant (left) and DSG solar power plant	7
Figure 1.6	Schematic of the once-through mode of the DSG process	8
Figure 1.7	Schematic of recirculation mode of the DSG process	9
Figure 1.8	Schematic of injection mode of the DSG process	10
Figure 2.1	Photograph of a PTSC row of the DISS test facility	17
Figure 2.2	Schematic diagram of 5 MWe INDITEP solar power plant	20
Figure 2.3	Flow patterns in the DSG process in the absorber tube of PTSC	26
Figure 2.4	Flow pattern maps for DSG in solar collector: (a) $p = 6.25$ MPa, $T_{in} = 239$ K, $\dot{m} = 0.55$ kg/s, and $DNI = 971$ W/m ² ; (b) $p = 10.19$ MPa, $T_{in} = 237$ K, $\dot{m} = 0.59$ kg/s, and $DNI = 960$ W/m ²	29
Figure 2.5	Various modes of heat losses from PTSC	31
Figure 2.6	Heat losses from the solar collector	32
Figure 2.7	East-west tracking of parabolic trough solar collector	46
Figure 2.8	Schematic of the stratified flow regime in the evaporation section of a PTSC row used for DSG	47
Figure 2.9	Magnified view of bending in the absorber tube of PTSC receiver	50
Figure 3.1	Geometric representation of the computational domain	69

Figure 3.2	The non-uniform concentrated heat flux profile around the absorber surface	69
Figure 3.3	View of mesh generated (a) cross-sectional view and (b) isometric view	72
Figure 3.4	Grid independent test: Variations of pressure loss and VVF with the total number of computational cells	72
Figure 3.5	Comparison of pressure variation with the experimental data of Reynolds	74
Figure 3.6	Comparison of VVF with the experimental data of Bartolomei et al., (1982) and numerical data of Maytorena and Hinojosa, (2019)	75
Figure 3.7	Variations in VVF along the tube length for 30 bar operating pressure	77
Figure 3.8	Variations in VVF along the tube length for 60 bar operating pressure	77
Figure 3.9	Variations in VVF along the tube length for 100 bar operating pressure	78
Figure 3.10	Contours of vapor volume fraction at axial positions 3 m, 6 m, 9 m, and 12 m for MFRs 0.3 kg/s to 0.6 kg/s and operating pressure of 30 bar	79
Figure 3.11	Variations in tube wall temperature around the circumference at various axial positions for MFRs (a) 0.3 kg/s, (b) 0.4 kg/s, (c) 0.5 kg/s and (d) 0.6 kg/s at 30 bar operating pressure	81
Figure 3.12	Variations in tube wall temperature around the circumference at various axial positions for MFRs (a) 0.3 kg/s, (b) 0.4 kg/s, (c) 0.5 kg/s and (d) 0.6 kg/s at 60 bar operating pressure	83
Figure 3.13	Variations in tube wall temperature around the circumference at various axial position for MFRs (a) 0.3 kg/s, (b) 0.4 kg/s, (c) 0.5 kg/s and (d) 0.6 kg/s at 100 bar operating pressure	85
Figure 3.14	Contours of tube wall temperature at axial positions 3 m, 6 m, 9 m, and 12 m from the inlet for MFRs 0.3 kg/s to 0.6 kg/s and operating pressure of 30 bar	87

Figure 3.15	Contours of tube wall temperature at axial positions 3 m, 6 m, 9 m, and 12 m from the inlet for MFRs 0.3 kg/s to 0.6 kg/s and operating pressure of 60 bar	88
Figure 3.16	Contours of tube wall temperature at axial positions 3 m, 6 m, 9 m, and 12 m from the inlet for MFRs 0.3 kg/s to 0.6 kg/s and operating pressure of 100 bar	89
Figure 3.17	Variation of the mixture velocity in the axial direction for various MFRs at the operating pressure of 30 bar	90
Figure 3.18	Variation of the mixture velocity in the axial direction for various MFRs at the operating pressure of 60 bar	91
Figure 3.19	Variation of the mixture velocity in the axial direction for various MFRs at the operating pressure of 100 bar	91
Figure 3.20	Liquid and vapor velocities variation in the axial direction for the MFR of 0.4 kg/s and operating pressure of 30 bar	92
Figure 3.21	Pressure drop variation with the change of the MFR	93
Figure 3.22	Circumferential wall temperature around the absorber's surface for operating pressure of 30 bar and MFRs: (a) 0.3 kg/s, (b) 0.4 kg/s, (c) 0.5 kg/s, and (d) 0.6 kg/s	95
Figure 3.23	Circumferential wall temperature around the absorber surface for operating pressure of 60 bar and MFRs: (a) 0.3 kg/s, (b) 0.4 kg/s, (c) 0.5 kg/s, and (d) 0.6 kg/s	97
Figure 3.24	Circumferential wall temperature around the absorber's surface for operating pressure of 100 bar and MFRs: (a) 0.3 kg/s, (b) 0.4 kg/s, (c) 0.5 kg/s, and (d) 0.6 kg/s	99
Figure 3.25	Contours of wall temperature at axial positions 3 m, 6 m, 9 m, and 12 m for operating pressure 30 bar	100
Figure 3.26	Contours of wall temperature at axial positions 3 m, 6 m, 9 m, and 12 m for operating pressure 60 bar	101
Figure 3.27	Contours of wall temperature at axial positions 3 m, 6 m, 9 m, and 12 m for operating pressure 100 bar	102
Figure 4.1	Position of CSF profile around the AOS at various times of the day	107

Figure 4.2	Geometric representation of the computational domain	109
Figure 4.3	The non-uniform CSF profile around the AOS for DNI of 750 W/m^2	109
Figure 4.4	The non-uniform CSF profile around the AOS for DNI of 1000 W/m^2	110
Figure 4.5	Contours of vapor volume fraction at various axial positions for DNI of 750 W/m^2 , mass flow rate of 0.4 kg/s , and operating pressure of 60 bar	112
Figure 4.6	Variation of VVF along the absorber length at solar noon	113
Figure 4.7	Outer surface temperature of the absorber at its outlet for DNI = 750 W/m^2 and $p = 60 \text{ bar}$	115
Figure 4.8	Outer surface temperature of the absorber at its outlet for DNI = 750 W/m^2 and $p = 100 \text{ bar}$	116
Figure 4.9	Outer surface temperature of the absorber at its outlet for DNI = 1000 W/m^2 , and $p = 60 \text{ bar}$	117
Figure 4.10	Outer surface temperature of the absorber at its outlet for DNI = 1000 W/m^2 , and $p = 100 \text{ bar}$	118
Figure 4.11	Variation of ΔT along the absorber length for DNI = 750 W/m^2 and $p = 60 \text{ bar}$	120
Figure 4.12	Variation of ΔT along the absorber length for DNI = 750 W/m^2 and $p = 100 \text{ bar}$	121
Figure 4.13	Variation of ΔT along the absorber length for DNI = 1000 W/m^2 and $p = 60 \text{ bar}$	122
Figure 4.14	Variation of ΔT along the absorber length for DNI = 1000 W/m^2 and $p = 100$	123
Figure 4.15	Contours of AWT at the $x = 0 \text{ m}$ (inlet), $x = 6 \text{ m}$ (middle of the absorber) and $x = 12 \text{ m}$ (outlet) for DNI = 750 W/m^2 , $p = 60 \text{ bar}$ and $\dot{m} = 0.4 \text{ kg/s}$	124
Figure 4.16	Contours of AWT at $x = 0 \text{ m}$ (inlet), $x = 6 \text{ m}$ (middle of the absorber) and $x = 12 \text{ m}$ (outlet) for DNI = 750 W/m^2 , pressure = 60 bar and $\dot{m} = 0.6 \text{ kg/s}$	124

Figure 4.17	Contours of AWT at $x = 0$ m (inlet), $x = 6$ m (middle of the absorber) and $x = 12$ m (outlet) for $\text{DNI} = 750 \text{ W/m}^2$, $p = 100$ bar and $\dot{m} = 0.4 \text{ kg/s}$	125
Figure 4.18	Contours of AWT at $x = 0$ m (inlet), $x = 6$ m (middle of the absorber) and $x = 12$ m (outlet) for $\text{DNI} = 750 \text{ W/m}^2$, $p = 100$ bar and $\dot{m} = 0.6 \text{ kg/s}$	125
Figure 4.19	Contours of AWT at the $x = 0$ m (inlet), $x = 6$ m (middle of the absorber) and $x = 12$ m (outlet) for $\text{DNI} = 1000 \text{ W/m}^2$, $p = 60$ bar and $\dot{m} = 0.4 \text{ kg/s}$	126
Figure 4.20	Contours of AWT at the $x = 0$ m (inlet), $x = 6$ m (middle of the absorber) and $x = 12$ m (outlet) for $\text{DNI} = 1000 \text{ W/m}^2$, $p = 60$ bar and $\dot{m} = 0.6 \text{ kg/s}$	126
Figure 4.21	Contours of AWT at $x = 0$ m (inlet), $x = 6$ m (middle of the absorber) and $x = 12$ m (outlet) for $\text{DNI} = 1000 \text{ W/m}^2$, $p = 100$ bar and $\dot{m} = 0.4 \text{ kg/s}$	127
Figure 4.22	Contours of AWT at $x = 0$ m (inlet), $x = 6$ m (middle of the absorber) and $x = 12$ m (outlet) for $\text{DNI} = 1000 \text{ W/m}^2$, $p = 100$ bar and $\dot{m} = 0.6 \text{ kg/s}$	127
Figure 5.1	Schematic of the DISS test facility	133
Figure 5.2	Schematic of PTSC row with the once-through operation mode	135
Figure 5.3	Geometrical schematic of the computational domain	136
Figure 5.4	The heat flux distribution at the absorber surface for DNI of 750 W/m^2	137
Figure 5.5	Fluid temperature variation along the length of the absorber tube	139
Figure 5.6	Comparison of pressure variation along the length of the absorber tube	140
Figure 5.7	Fluid mixture temperature variation along the length of the absorber tube	142
Figure 5.8	Variation of steam quality along the length of the absorber tube	143
Figure 5.9	Absorber circumferential temperature distribution under operating pressure of 60 bar at axial positions (a) 0 m, (b) 100 m, (c) 200 m, (d) 300 m, (e) 400 m, and (f) 500 m	146

Figure 5.10	Absorber circumferential temperature distribution under operating pressure of 100 bar at axial positions (a) 0 m, (b) 100 m, (c) 200 m, (d) 300 m, (e) 400 m, and (f) 500 m	149
Figure 5.11	Contours of absorber temperature under operating pressure of 60 bar at axial positions (a) 0 m, (b) 100 m, (c) 200 m, (d) 300 m, (e) 400 m, and (f) 500 m	152
Figure 5.12	Contours of absorber temperature under operating pressure of 60 bar at axial positions (a) 0 m, (b) 100 m, (c) 200 m, (d) 300 m, (e) 400 m, and (f) 500 m	154
Figure 5.13	Distribution of CTD in the axial direction at an OP of 60 bar	155
Figure 5.14	Distribution of CTD in the axial direction at an OP of 100 bar	155
Figure 5.15	Variation of fluid mixture velocity along the length of the absorber	156
Figure 5.16	Variation of pressure along the length of the absorber	157
Figure 6.1	Geometric view of the grooves	161
Figure 6.2	Computational domain and boundary conditions	164
Figure 6.3	Schematic of the grooved absorber tube	164
Figure 6.4	Computational domain considered for CFD simulations	165
Figure 6.5	View of the generated mesh	166
Figure 6.6	Variation of VVF along the length for operating pressure of 60 bar	169
Figure 6.7	Variation of VVF along the length for operating pressure of 100 bar	169
Figure 6.8	Circumferential temperature distributions at outer surface of the absorber tube at 60 bar operating pressure for mass flow rates of (a) 0.4 kg/s, and (b) 0.6 kg/s	171
Figure 6.9	Circumferential temperature distributions at outer surface of the absorber tube at 100 bar operating pressure for mass flow rates of (a) 0.4 kg/s, and (b) 0.6 kg/s	172
Figure 6.10	Temperature contours in absorber wall at 60 bar operating pressure	173
Figure 6.11	Temperature contours in absorber wall at 100 bar operating pressure	174
Figure 6.12	Pressure loss with the length for operating pressure of 60 bar	174
Figure 6.13	Pressure loss with the length for operating pressure of 100 bar	175
Figure 7.1	Real photograph of deflected absorber	178

Figure 7.2	Schematic of the computational domain with boundary conditions for thermal-hydraulic analysis	186
Figure 7.3	Schematic representation of boundary conditions implemented on the absorber for structural analysis	188
Figure 7.4	Computational mesh for (a) thermal-hydraulic analysis and (b) structural analysis	189
Figure 7.5	Comparison of absorber surface temperature distribution with DISS experimental data and numerical data of Serrano-Aguilera et al. (2014)	191
Figure 7.6	Validation of deflection in absorber with an analytical model of Khanna et al. (2015)	192
Figure 7.7	Circumferential temperature distribution at mid ($x = 2.03$) of the absorber at operating pressures of (a) 60 bar and (b) 100 bar	194
Figure 7.8	Deflection in absorber at operating pressures of (a) 60 bar and (b) 100 bar	195
Figure 7.9	Thermal strain in steel absorber along an axial line at the bottom of the absorber at operating pressures of (a) 60 bar and (b) 100 bar	197
Figure 7.10	Axial stress in steel absorber along an axial line at the top of the absorber at operating pressures of (a) 60 bar and (b) 100 bar	198
Figure 7.11	Axial stress in steel absorber along an axial line at the bottom of the absorber at operating pressures of (a) 60 bar and (b) 100 bar	199
Figure 7.12	Circumferential stress in steel absorber along a line at the top of the absorber at operating pressures of (a) 60 bar and (b) 100 bar	201
Figure 7.13	Circumferential stress in steel absorber along a line at the bottom of the absorber at operating pressures of (a) 60 bar and (b) 100 bar	202
Figure 7.14	Circumferential stress in steel absorber along a line around the circumference at mid of the absorber at operating pressures of (a) 60 bar and (b) 100 bar	203
Figure 7.15	Equivalent stress in steel absorber along an axial line at the top of the absorber at operating pressures of (a) 60 bar and (b) 100 bar	204

Figure 7.16	Equivalent stress in steel absorber along an axial line at the bottom of the absorber at operating pressure of (a) 60 bar and (b) 100 bar	205
Figure 7.17	Equivalent stress in steel absorber along a line around the circumference at mid of the absorber at operating pressures of (a) 60 bar and (b) 100 bar	206

List of Tables

Table No.	Title of Table	Page No.
Table 2.1	Summary of R & D projects on the development of DSG technology	15
Table 2.2	Specifications of the DISS solar field	18
Table 2.3	Operating conditions of the DISS solar field	18
Table 2.4	Specifications of the INDITEP solar field	21
Table 2.5	Operating conditions defined for the INDITEP project	21
Table 2.6	Summary of observation of flow pattern maps in DSG solar collectors	30
Table 2.7	Various thermo-hydraulic models for two-phase flow	34
Table 2.8	Summary of HEM modeling of DSG available and in the literature	36
Table 2.9	Summary of TFM modeling of DSG	44
Table 3.1	Specifications of parabolic trough solar collector system	68
Table 3.2	Thermophysical properties of water and vapor at saturation temperature	71
Table 3.3	Experimental data for model validation	74
Table 3.4	The maximum circumferential temperature difference in the tube wall subjected to uniform heat flux distribution	86
Table 3.5	The maximum circumferential temperature difference in the tube wall at solar noon subjected to non-uniform heat flux distribution	103
Table 4.1	The value of the maximum and minimum absorber surface temperature	128
Table 5.1	Technical specifications of north-south oriented PTSC based DISS test facility installed at PSA, Spain (37°05'28" N and 2°21'19" W)	134
Table 5.2	DISS test facility operating conditions	139
Table 6.1	Characteristic parameters of grooves	161
Table 6.2	Geometric configurations of the grooved absorber and operating conditions	163
Table 6.3	Comparison of heat transfer in the absorber with and without grooves at 60 bar operating pressure	168

Table 6.4	Comparison of heat transfer in the absorber with and without grooves at 100 bar operating pressure	168
Table 6.5	Comparison of total pressure loss	175
Table 6.6	Comparison of thermal-hydraulic parameters of conventional and grooved absorber for DSG	176
Table 7.1	Thermophysical properties of air present in the annulus of PTC receiver	178
Table 7.2	Parameters of parabolic trough solar collector	185
Table 7.3	Absorber material properties	185
Table 7.4	Comparison of present model results with DISS experimental data and numerical data	190

Nomenclature

Symbols

A	Interfacial area (m^2)
a	Absorption coefficient
C_p	Specific heat capacity ($\text{Jkg}^{-1}\text{K}^{-1}$)
$D_{i,a}$	Absorber inner diameter (m)
$D_{i,e}$	Glass envelop inner diameter (m)
$D_{o,a}$	Absorber outer diameter (m)
F_{lift}	Lift force (N)
F_{td}	Turbulent dispersion force (N)
F_{vm}	Virtual mass force (N)
F_{wl}	Wall lubrication force (N)
g	Acceleration due to gravity (ms^{-2})
h	Heat transfer coefficients ($\text{Wm}^{-2}\text{K}^{-1}$)
I	Radiation intensity (Wm^{-2})
K	Turbulent kinetic energy (Jkg^{-1})
K_{eff}	Effective thermal conductivity of Annulus ($\text{Wm}^{-1}\text{K}^{-1}$)
K_{std}	Thermal conductivity of air ($\text{Wm}^{-1}\text{K}^{-1}$)
L	Length (m)
LH	Latent heat (Jkg^{-1})
\dot{m}	Mass flow rate (kgs^{-1})
n	Refractive index
\vec{n}_w	Unit normal vector perpendicular to the wall

p	Pressure (Pa)
p_a	Annulus pressure (Torr)
\dot{q}	Heat flux (Wm^{-2})
\dot{q}_c	Forced convection heat flux to the liquid phase (Wm^{-2})
\dot{q}_E	Evaporative heat flux (Wm^{-2})
\dot{q}_F	Boiling heat flux to thin film (Wm^{-2})
\dot{q}_Q	Quenching heat flux (Wm^{-2})
\dot{q}_V	Forced convection heat flux to the vapor phase (Wm^{-2})
r	Radius (m)
\vec{r}	Position vector
s	Path length
\vec{s}	Direction vector
\vec{s}'	Scattering direction vector
t	Time (s)
T	Temperature (K)
$T_{a,o}$	Absorber outer surface temperature (K)
$T_{e,i}$	Glass envelop inner surface temperature (K)
v	Velocity magnitude (ms^{-1})
\vec{v}	Overall velocity vector (ms^{-1})
V	Volume (m^3)

Greek symbols

α	Phase volume fraction
δ	Molecular diameter (cm)

γ	Ratio of specific heat capacity
λ	Mean free path between collision of air molecules (cm)
η	Accommodation coefficient for gas-solid interaction
ω	General interfacial quantities
ρ	Density (kgm^{-3})
μ	Dynamic viscosity (Nsm^{-2})
Γ	Coefficient of diffusion
Ω'	Solid angle (Steradian)
ϕ	Phase function
σ	Stefan-Boltzmann constant
σ_s	Scattering coefficient
θ	Angle (degree)

Subscripts

i	Interface
in	Inlet
l	Liquid phase
sat	Saturation temperature
v	Vapor phase
w	Wall
t	Turbulence (m^2)

Abbreviations

AOS	Absorber Outer Surface
ARDISS	Advanced Receiver for Direct Solar Steam

ATHLET	Analysis of Thermal-hydraulics of leaks and transients
ATS	Advanced Trough System
BM	Boiling model
BOP	Balance of plant
CFD	Computational fluid dynamics
CHF	Critical heat flux
CIEMAT	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
CR	Central receiver
CSF	Concentrating solar flux
CSP	Concentrating solar power
CTD	Circumferential temperature difference
DISS	Direct Solar Steam
DNI	Direct normal irradiation
DLR	Deutschen Zentrum für Luft und Raumfahrt
DO	Discrete ordinates
DSG	Direct steam generation
DUKE	DUKE Durchlaufkonzept –Entwicklung und Erprobung
EMM	Eulerian multiphase model
ET	EuroTrough
FDM	Finite difference method
FEM	Finite element method
FVM	Finite volume method
GDP	Gross domestic product

GDV	Generación Directa de Vapor
GHI	Global horizontal irradiation
GUDE	Grundlegende Untersuchungen zur solaresDirektverdampfung von wasser nach dem Einspritzprinzip
HEM	Homogeneous equilibrium model
HIPRESS	High-Pressure Experiments
HT	Heat transfer
HTC	Heat transfer coefficient
HTF	Heat transfer fluid
INDITEP	Integration of DSG technology for electricity production
INETI	Instituto Nacional de Engenharia e Tecnologia Industrial
ISE	Institute for Solar Energy
ISG	Indirect steam generation
LCOE	Levelized cost of electricity
LFR	Linear Fresnel reflector
LP	Liquid phase
LPM	Lumped parameter method
MBM	Moving boundary method
MCRT	Monte Carlo ray tracing
MFR	Mass flow rate
MOL	Method of line
MT	Mass transfer
NCSP	Non-concentrated solar power

NREL	National Renewable Energy Laboratory
OECD	Organization of economic co-operation and development
ONV	Onset of nucleate
OP	Operating Pressure
PCM	Phase change material
PDC	Parabolic dish collector
PTSC	Parabolic trough solar collector
RELAP	Reactor Excursion and Leak Analysis Program
RPI	Rensselaer Polytechnic Institute
SC	Solar collector
SEGS	Solar electric generation systems
SERI	Solar Energy Research Institute
SPT	Solar power tower
STEM	Solar Thermal Electricity for Mediterranean Countries
TD	Temperature distribution
TES	Thermal energy storage
TFM	Two-fluid model
TPF	Two-phase flow
TSE-1	Thai Solar One
TUM	Technische Universität München
UDF	User-defined function
UEM	Union electrica fenosa
UMIST	University of Manchester Institute of Science and Technology

VOF	Volume of fluid
VP	Vapor phase
VVF	Vapor volume fraction
ZSW	Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg