LABORATOIRE
PROCÉDÉS, MATÉRIAUX
et ENERGIE SOLAIRE
.UPR 8521 du CNRS.
conventionnée avec
l'université de Perpignan
PROCESSES,MATERIALS
and SOLAR ENERGY
LABORATORY

MODULE HANDBOOK

European Master in Renewable energy

SPECIALISATION "STARS"

Solar Thermal & Associated Renewable Storage

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PROMES-CNRS

June 2020

Module 1/:Solar Thermal: FUNDAMENTALS

Module name:	**Fundamentals**
Section	EUREC spectialisation solar thermal
Classes	**Reminder** Heat transfer Materials **Combined heat and mass transfer** Conduction : Fundamental Equations ,Balance equations ,Examples Convection : Fundamental Equations Forced Convection (resolution of the Couette flow with temperature) Natural Convection (approximation of Boussinesq) Introduction to CFD **Radiative heat transfer** Fundamentals of Thermal Radiation Radiative Exchange between Surfaces Radiative properties of opaque surfaces View factors Radiative exchange between grey and diffuse surfaces Equation of Radiative Transfer in Participating Media Radiative Properties of Participating Media Radiative properties of molecular gases Radiative properties of particulate media Radiative Transfer through Participating Media

Semester	2nd Semester
Module Coodinator	Dr. Maxime Perier-Muzet
Lecturers	Dr. Maxime Perier-Muzet, Dr Quentin Falcoz, Occasional external lecturers,
Language	English

Classification within the curriculum	Specialization in Solar thermal
Teaching format / class hours during the semester	35 h Lecture Tutorial 25 h Laboratory
Contact Hours/ Workload	60 h (Contact hours) 200 h (total time of studying)
Credit points	6
Requirements under the examination regulations	
Recommended prerequisites (prior knowledge	Basic Understanding in • Thermodynamics • Energy and Thermal Science • Electromagnetics • Materials • Fluid dynamics
Target learning outcomes	The module *fundamentals* teaches the theoretical basis of radiation models to be used in solar engineering processes. **Objectives** 1. To develop the student‘s understanding of the principles and the modelling approaches of combined heat and mass transfer in solar processes. 2. To develop the student‘s understanding of the effect of radiation in a solar process. 3. To develop the student‘s understanding of the radiative heat transfer methods of resolution to be used in solar applications. 4. To develop the student‘s understanding of the various assumptions and computing efficiency of radiation models. 5. To develop the student‘s understanding of the models limitations to practical uses. 6. To develop the student‘s knowledge of the main radiative properties of materials used in solar processes. 7. To develop the student‘s awareness of the important development in radiation measurement. 8. To develop the student‘s knowledge of the optical measurement issues. **Awareness/Competences** 1. The student will have a critical understanding of the effect of radiation on fluid flows. 2. The student will have a critical understanding of radiation modelling in solar processes. 3. The student will have a critical understanding of the methodology that should be used in a practical situation where radiative heat transfer is to be solved, and coupled with other transfer modes. 4. The student will be able to compare and evaluate radiation simulation results from different models.

	5. The student will have a critical understanding of optical properties and their influences on radiation heat transfer. 6. The student will have a critical understanding of optical measurements. **On Relation to other Modules** This module is strongly related with all the other modules

Content	**<u>Part 1: Radiative heat transfer</u>**
	• Fundamentals of Thermal Radiation
	• Radiative Exchange between Surfaces
	  • Radiative properties of opaque surfaces
	  • View factors
	  • Radiative exchange between grey and diffuse surfaces
	• Equation of Radiative Transfer in Participating Media
	  • Equation of radiative transfer
	  • Formal solutions
	  • Boundary conditions
	• Radiative Properties of Participating Media
	  • Radiative properties of molecular gases
	  • Radiative properties of particulate media
	• Radiative Transfer through Participating Media
	  • Collimated irradiation
	  • The Two-Flux method
	  • The method of Discrete Ordinates
	  • The Monte Carlo method
	  • The Rosseland approximation
	  • The Diffusion approximation
	• High temperature measurements
	  • Pyrometry
	  • Infrared thermography
	<u>Part 2: Combined heat and mass transfer</u>
	• Conduction
	  • Fundamental Equations
	  • Balance equations
	  • Examples
	• Convection

	• Fundamental Equations • Forced Convection (resolution of the Couette flow with temperature) • Natural Convection (approximation of Boussinesq) • Adimensionnal equations • CFD sotfwares
Study/ exam achivements	Written examination on each part plus an extended laboratory report
Forms of media	Whiteboard, projector for PC, Blackboard electronic learning portal
Literature	Modest M. F., *Radiative Heat Transfer* (2003) Siegel R., Howell J.R. *Thermal Radiation Heat Transfer* (2002) Lesieur, *Turbulence in Fluids*, Kluwer Academic Publisher, 1997. James, Smith and Wolford , *Applied numerical methods for digital computation*, James, Smith and Wolford, Harper & Row, New-York.

Module 2/Solar thermal: **SIMULATION AND SYSTEM OPTIMIZATION**

Module name:	**SIMULATION AND SYSTEM OPTIMIZATION**
Section	EUREC Specialisation Solar Thermal
Classes	**Part 1: Solar Conversion (solar heating/cooling, microgeneration)** ➢ Solar water heating ➢ Solar air heating ➢ Combined Solar System ➢ Design softwares ➢ Solar cooling :Liquid Absorption technology ➢ Solar cooling :Solid sorption technology Microgeneration system : ORC working at low temperature. **Part 2: Solar concentrating systems and receiver** ➢ The solar resource for concentrating systems: solar spectrum, solar constant and air mass ➢ Introduction to concentration optics ➢ Linear concentration: parabolic trough and linear Fresnel ➢ Point concentration: Dish and Tower (Central receiver systems) ➢ High concentration systems: solar furnace and compound parabolic concentrator (CPC) ➢ Design and technology of radiative selective surfaces for solar receivers ➢ Design and technology of solar receivers (absorbers) for linear concentrators ➢ Design and technology of solar receivers for point focusing systems ➢

Semester	2nd Semester
Module Coordinator	Pr Pierre Neveu
Lecturers	Pr. Pierre Neveu, Dr Arnaud Perona, Dr. Maxime Perier-Muzet Occasional external speakers
Language	English
Classification within the curriculum	Specialization in Solar thermal

<table>
<tr><td>Teaching format / class hours during the semester</td><td>30 h
20 h
10 h
6 h total</td><td>Lecture
Tutorials
Laboratories
Visits</td><td>All aspects of the module</td></tr>
<tr><td>Contact Hours/ Workload</td><td colspan="3">60 h (Contact hours)
200 h (total time of studying)</td></tr>
<tr><td>Credit points</td><td colspan="3">6</td></tr>
<tr><td>Requirements under the examination regulations</td><td colspan="3"></td></tr>
<tr><td>Recommended prerequisites (prior knowledge</td><td colspan="3">Basic Understanding in
• Heat Transfer
• Thermodynamics
• Energy in buildings</td></tr>
<tr><td>Target learning outcomes</td><td colspan="3">Objectives
1. To develop the student‘s awareness of the potentialities of solar resource for energy saving in building
2. To develop the student’s awareness of the solar heating and cooling technologies
3. To develop the student‘s understanding of the thermodynamics of energy conversion systems
4. To familiarize the student with the utilisation of different numeric tools for heating systems design, performance evaluation and techno-economic viability
Awareness/Competences

1. The student will be able to compare the design and operation of solar heating and/or cooling systems in buildings
2. The student will have a critical understanding of the complete system efficiency on the basis of sub-systems efficiency limitation.

On Relation to other Modules
This module is related to the modules Fundamentals</td></tr>
<tr><td>Content</td><td colspan="3"><u>Part 2: Solar Conversion (solar heating/cooling, microgeneration)</u>
• Thermodynamics optimisation : exergy analysis
• Potentialities of low temperature solar energy for cooling
• Potentialities of low temperature solar energy for electriciy production
• Heat driven cooling system theory and thechnologies
- Liquid absorption system</td></tr>
</table>

	- Solid sorption systems • Microgeneration : ORC and Stirling systems **Part 2 : Solar concentrating systems and receiver** • The solar resource for concentrating systems • Introduction to concentration optics • Linear concentration: trough and linear Fresnel • Point concentration: Dish and Tower (Central receiver systems) • High concentration systems: solar furnace and compound parabolic concentrator (CPC) • Selective surfaces for solar receiver • Solar receivers (absorbers) for linear concentrators •
Study/ exam achivements	Written examination on each part plus an extended laboratory report
Forms of media	Whiteboard, projector for PC, Blackboard electronic learning portal
Literature	Renewable Energy, B. Sorensen. Elsevier, 2004. Applied thermodynamics,, Richard E. Sonntag , Gordon J. Van Wylen, ERPI, 2004

Module 3/Solar thermal: ENERGY

Module name:	ENERGY
Section	EUREC Specialisation Solar Thermal
Classes	**<u>Part 1: Solar Collectors theory and technologies</u>** ➢ Energy collection and heat transfer in solar collectors – characteristics of materials ➢ Design and simulation ➢ Overview of the solar collectors technologies ➢ Implementation ➢ Design software **<u>Part 2: Solar power plants</u>** ➢ Introduction to Concentrating Solar Power (CSP): various options, plants in operation, industry ➢ Numeric tools for CSP design and performance evaluation: Soltrace, Tonathiu and home-made codes ➢ Case study and visit of solar power plants (Themis) ➢ Cogeneration systems: electricity and heat, electricity and water ➢ Tools for CSP design and performance evaluation ➢ Techno-economics of CSP ➢ Case study: Parabolic trough plant ➢ Case study: Central receiver plant ➢ Case study: Dish-engine plant ➢ Cogeneration systems

Semester	2nd Semester		
Module Coordinator	Dr. Quentin Falcoz		
Lecturers	Dr. Gilles Flamant, Dr. Alain Ferrière, Dr. Quentin Falcoz Occasional external speakers as appropriate		
Language	English		
Classification within the curriculum	Specialization in Solar thermal		
Teaching format / class hours during the semester	35 h 15 h 10 h	Lecture Tutorials Laboratories	All aspects of the module

<table>
<tr><td></td><td>10 h</td><td>Visits</td><td></td></tr>
<tr><td>Contact Hours/ Workload</td><td colspan="3">60 h (Contact hours)
200 h (total time of studying)</td></tr>
<tr><td>Credit points</td><td colspan="3">6</td></tr>
<tr><td>Requirements under the examination regulations</td><td colspan="3"></td></tr>
<tr><td>Recommended prerequisites (prior knowledge</td><td colspan="3">Basic Understanding in
• Thermal Transfers
• Optics
• Thermodynamics</td></tr>
<tr><td>Target learning outcomes</td><td colspan="3">Objectives
1. To develop the student‘s awareness of the potentialities of concentrated solar resource for electricity production
2. To develop the student‘s understanding of the different solar collectors systems
4. To familiarize the student with the utilisation of different numeric tools for CSP design, performance evaluation and techno-economic viability
Awareness/Competences
1. The student will have a critical understanding of the physical principles relating to the operation and design of concentrating systems, solar receivers and concentrated solar plants.
2. The student will be able to compare the design and operation of concentrating systems, solar receivers and concentrated solar plants.
3. The student will have a critical understanding on the influence of the design and performance of concentrating systems on solar receivers.
5. The student will have a critical understanding of the complete system efficiency on the basis of sub-systems efficiency limitation.
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On Relation to other Modules
This module is strongly related to the Fundamentals.</td></tr>
<tr><td>Content</td><td colspan="3">Part 1 : Solar Collectors theory and technologies
• The solar resource
- Direct and indirect irradiance
- Mask effects
• Solar collectors theory
- Plate collectors</td></tr>
</table>

	- Evacuated collectors - Low concentrated collectors • Solar collectors technologies and application • Design software for implantation in buildings. **Part 2 : Solar power plant** • Introduction to Concentrating Solar Power (CSP): various options, plants in operation, industry • Tools for CSP design and performance evaluation • Techno-economics of CSP • Case study: Parabolic trough plant • Case study: Central receiver plant • Case study: Dish-engine plant • Cogeneration systems: electricity and heat, electricity and water
Study/ exam achivements	Written examination on each part plus an extended laboratory report
Forms of media	Whiteboard, projector for PC
Literature	Journal of Solar Energy Engineering Proceedings of SolarPACES Piatkowski N. et al. *Energy and Environmental Science* (2011), 4, 73 Abanades S. et al. *Energy* (2006) 31, 2469 W. Chueh et al. *Science*, (2010) 330, 1797 Schunk L.O. et al. *Chemical Engineering Journal* (2009) 150, 502 Maag G. et al. *International Journal of Hydrogen Energy* (2010), 35, 13232

Module 4/Solar thermal: *RENEWABLE STORAGE*

Module name:	**RENEWABLE STORAGE**
Section	EUREC specialisation in Solar Thermal
Classes	**Part 1: Thermal Storage** ➢ Overview of thermal storage (TS) ➢ Needs of TS in solar applications ➢ Available technologies (sensible, latent heat, thermochemical, ...) ➢ Related materials ➢ Heat transfer interfaces and fluids ➢ Implementation of TS ➢ Management and strategy of TS ➢ Related companies and products **Part 2: Solar fuels** ➢ General introduction, chemical routes to produce solar fuels from solar energy ➢ Thermodynamics of solar fuel production ➢ Hybrid thermochemical routes, solar and carbonaceous materials -NG, coal, wastes, biomass ➢ Renewable thermochemical route, the solar-biomass case study ➢ Solar-only thermochemical routes, Redox systems –thermodynamics and materials issues ➢ Solar-only thermochemical routes, Metal oxides case study ➢ Solar receivers-reactors

Semester	2nd Semester	
Module Coodinator	Dr Samuel Mer	
Lecturers	Dr Samuel Mer, Dr Sylvain Rodat, Dr Gilles Flamant	
Language	English	
Classification within the curriculum	Specialization in Solar thermal	
Teaching format / class hours during the semester	30 h 15 h 5 h	Lecture Tutorial Laboratories
Contact Hours/ Workload	60 h (Contact hours) 200 h (total time of studying)	

Credit points	6
Requirements under the examination regulations	
Recommended prerequisites (prior knowledge	Basic Understanding in • thermodynamics • thermal and energy science and engineering • materials • chemistry
Target learning outcomes	From Part1, the student will be familiar with main storage materials and technologies and will be able to choose which one is the most adapted to a specific solar application**.** Part 2 teaches the principles of thermochemistry and process engineering to produce either gaseous or liquid fuels using concentrated solar energy and resource of C, H, O elements. **Objectives** 1. To develop the student‘s understanding of the basic physical phenomena relevant to the principles of operation and design of thermal energy storages. 2. To develop the student‘s understanding of the principles of operation and design of thermal energy storages. 3. To develop the student‘s understanding of the need to define properly the functionalities of the TES. 4. To develop the student‘s knowledge of the main technologies and materials used in TES. 5. To develop the student‘s awareness of the importance of considering the relevant integration of TES in the whole process of application. 6. To develop the student‘s awareness of the importance of strategy and management in the use of TES. 7. To develop the student‘s knowledge of the main companies involved in the various aspects of TES (material, envelopes, fluids). To develop the student‘s understanding of the thermodynamics of chemical reactions that lead to fuels production from solar heat. **Awareness/Competences** 1. The student will have a critical understanding of the physical principles used in TES. 2. The student will be able to compare the design, operation and performances of the main types of TES. 3. The student will be able to choose the relevant TES for a particular application. 4. The student will be able to highlight the main limitations of a TES. 5. The student will be able to avoid the usual mistakes encountered in TES. 6. The student will be able to propose companies providing the various components of TES. 7. The student will have a critical understanding of the thermodynamic limitation of solar fuels production 8. The student will have a critical understanding of the complete system efficiency on the basis of sub-systems efficiency limitation. 9. The student will be able to compare and evaluate different chemical pathways with respect to solar energy stored in the chemicals and to CO_2 mitigation impact.

	10. The student will have a critical understanding of the principles of solar thermochemical reactor design and modeling. 11. The student will be able to compare and evaluate various solar thermochemical and thermodynamical processes. **On Relation to other Modules** This module is in direct relations with the 3 first ones.
Content	 **<u>Part1 Thermal Storage</u>** **Overview on Thermal Energy Storage (TES)** ➢ TES definitions ➢ TES functionalities ➢ TES basic principles ➢ TES technologies ➢ ES hybridations ➢ ES bottle-necks and current research areas **Needs of TES in solar applications** ➢ Resource/demand shift management ➢ Thermal protection ➢ Thermal regulation ➢ Production optimisation ➢ Process design optimisation ➢ Process management **Available technologies (sensible, latent heat, thermochemical)** ➢ Sensible heat based TES, direct mode. ➢ Sensible heat based TES, indirect mode. ➢ Latent heat based TES (organic, inorganic) ➢ Thermochemical based TES **Related materials** ➢ Low temperature TES materials Sensible heat, latent heat, thermochemical Classifications and properties, characterizations ➢ High temperature TES materials Sensible heat, latent heat, thermochemical Classifications and properties, characterizations **Heat transfer interfaces and fluids**

- Envelops for TES units
- Insulating materials for TES units
- Heat transfer fluids for TES

Implementation of TS

- TES integration
- TES instrumentation
- TES charge/discharge assessments

Management and strategy of TS

- TES management
- TES strategy
- LTA of TES in Solar Applications

Related companies and products

- Companies and products for sensible heat based TES
- Companies and products for latent heat based TES
- Companies and products for thermochemical TES
- Companies and products for envelopes and connections

<u>Part 3 : Solar fuels</u>

- Thermodynamics of chemical reactions
- Chemical pathways to hydrogen, methanol and hydrocarbons from water, carbon dioxide and carbonaceous materials
- Energy and exergy balances
- Energy and material balances when using natural gas, coal and biomass as Carbon resource
- Principle of Redox reaction to split H_2O and CO_2
- Various options for redox reactions
- Material and separation issues of the various options
- Thermodynamics and kinetics of the various redox reactions
- Principles of solar reactors
- Material issues in solar reactors
- Concentrating systems for high temperature solar thermochemistry
- Efficiency of a solar thermochemical process
- Case study as a function of the reaction temperature
- Lab-scale and pilot scale development, state of the art
- Solar thermochemitsry for industry

Study/ exam achivements	Written examination
Forms of media	Power point files
Literature	Fundamentals of Heat and Mass Transfer, F. P. Incropera, D.P. DeWitt ed., ISBN 0-471-30460-3. Fundamentals of renewable Energy Processes, A. V. Da Rosa, Elsevier ed., 2005, ISBN 0-12-088510-7. Thermal Energy Storage, I. Dincer, M.A. Rosen, Wiley ed., 2002, ISBN 0-471-49573-5. Solar Engineering of Thermal Processes, J.A. Duffie, W.A. Beckman, Wiley ed., 2006, ISBN 100-471-69867-9. Renewable Energy, B. Sorensen, Elsevier ed., 2004, ISBN 0-12-656153-2. Gil, A., Medrano, M., Martorell, I., Lazaro, A., Dolado, P., Zalba, B., and Cabeza, L.F., 2010, "State of the art on high temperature thermal energy storage for power generation. Part 1-Concepts, materials and modelization", Renew. and Sust. Energy Reviews, 14, pp. 31-55. Medrano, M., Gil, A., Martorell, I., Potau, X., and Cabeza, L.F., "State of the art on high temperature thermal energy storage for power generation. Part 2- Case studies", Renew. and Sust. Energy Reviews, 14, pp. 56-72. Journal of Solar Energy Engineering Proceedings of SolarPACES Piatkowski N. et al. *Energy and Environmental Science* (2011), 4, 73 Abanades S. et al. *Energy* (2006) 31, 2469 W. Chueh et al. *Science*, (2010) 330, 1797 Schunk L.O. et al. *Chemical Engineering Journal* (2009) 150, 502 Maag G. et al. *International Journal of Hydrogen Energy* (2010), 35, 13232

Module 5/Solar thermal: *PROJECT, CASE STUDY AND INNOVATION*

Module name:	**PROJECT, CASE STUDY AND INNOVATION**
Section	EUREC specialisation in Solar Thermal
Classes	**Part 1: Innovative materials for energy conversion** • Selective surfaces for solar receiver • Materials for low temperature solar application • Thermos optical properties of materials for solar thermal applications

	<u>Part 2: Project, case study</u> • Project • Case study: Parabolic trough plant • Case study: Central receiver plant • Case study: Dish-engine plant

Semester	2nd Semester
Module Coodinator	Dr Audrey Soum-Glaude
Lecturers	Dr Audrey Soum-Glaude, Prof Pierre Neveu, Dr Quentin Falcoz
Language	English
Classification within the curriculum	Specialization in Solar thermal
Teaching format / class hours per week during the semester	15 h Lecture 20 h Tutorial 5 h Laboratories
Contact Hours/ Workload	40 h (Contact hours) 200 h (total time of studying)
Credit points	6
Requirements under the examination regulations	
Recommended prerequisites (prior knowledge	Basic Understanding in • thermodynamics • thermal and energy science and engineering • materials
Target learning outcomes	The student will be familiar with innovative materials for energy conversion and able to choose which one is the most adapted for a specific solar application. He will be able to analyse different case study related to CSP technologies. After part 1 course, student will mainly be able to: • Identify the types of materials used in solar components and understand why they are selected; • Appreciate the key impact of the optical properties of these materials on the efficiency of solar applications, and how to improve the latter; • Understand how optical properties can be measured; • Calculate optical properties using standard software;

	• Assist and counsel in the optical design of components for solar thermal, in terms of optimizing their surface properties. **Objectives** 1. To develop the student‘s understanding of the basic physical phenomena relevant to the principles of thermos optical materials properties. 2. To develop the student‘s understanding of the principles of selective materials. 3. To develop the student‘s understanding of receiver materials under concentrated radiation. 4. To develop the student‘s knowledge of the main elaboration technologies and materials used in CSP. 5. To develop the student‘s awareness of the importance of materials constraints. 6. To develop the student‘s awareness about scale of the system. 7. To develop the student‘s awareness of the importance of case study. 8. To develop the student‘s awareness about real power plant. 6. To develop the student‘s skills about team working **Awareness/Competences** 1. The student will have a critical understanding of the physical principles involved materials used for solar receiver. 2. The student will be able to compare the design, operation and performances of the main types of selective coatings. 3. The student will be able to choose the relevant materials for a particular application. 4. The student will be able to highlight the main limitations of selective materials. 5. The student will be able to avoid the usual mistakes encountered in high temperature materials under high flux. 6. The student will be able to manage a small project. 7. The student will be able to understand main constraints related to a system scale analysis. 8. The student will be able to understand the main difficulties encountered in a real case of CSP power plant. **On Relation to other Modules** This module is strongly related to module 2 and 3
Content	**Part 1 Innovative materials for energy conversion** • Selective surfaces for solar receiver • Materials for low temperature solar application • Thermos optical properties of materials for solar thermal applications **Part 2 : Project, case study** • Project

	• Case study: Parabolic trough plant • Case study: Central receiver plant • Case study: Dish-engine plant
Study/ exam achivements	Written examination, project report, oral presentation
Forms of media	Power point files
Literature	C. Atkinson, C.L. Sansom, H.J. Almond, C.P. Shaw, Coatings for concentrating solar systems – A review, Renewable and Sustainable Energy Reviews. 45 (2015) 113–122. https://doi.org/10.1016/j.rser.2015.01.015. C.E. Kennedy, Review of Mid- to High-Temperature Solar Selective Absorber Materials, National Renewable Energy Lab., Golden, CO. (US), 2002. https://doi.org/10.2172/15000706. K. Xu, M. Du, L. Hao, J. Mi, Q. Yu, S. Li, A review of high-temperature selective absorbing coatings for solar thermal applications, Journal of Materiomics. 6 (2020) 167–182. https://doi.org/10.1016/j.jmat.2019.12.012. ESTELA (European Solar Thermal Electricity Association), www.estelasolar.org