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# 820765 - MTCM - Heat Engines and Combustion

Coordinating unit: 240 - ETSEIB - Barcelona School of Industrial Engineering
Teaching unit: 724 - MMT - Department of Heat Engines
Academic year: 2019
Degree: MASTER'S DEGREE IN ENERGY ENGINEERING (Syllabus 2013). (Teaching unit Optional)
MASTER'S DEGREE IN ENERGY ENGINEERING (Syllabus 2013). (Teaching unit Optional)
ECTS credits: 5 Teaching languages: Catalan, Spanish, English

## Teaching staff

Coordinator: Carles David Pérez Segarra

Others: Jordi Ventosa
Jesús Andrés Álvarez Flórez

## Opening hours

Timetable: The specific timetable is personally agreed on with the student according to his/her availability.

## Prior skills

Knowledge of fluid dynamics and heat and mass transfer, necessary to understand the functioning of heat engines.

## Requirements

Knowledge equivalent to having completed the course of levelling the Master's

## Degree competences to which the subject contributes

Specific:

CEMT-6. Employ technical and economic criteria to select the most appropriate electrical equipment for a given application, dimension thermal equipment and facilities, and recognise and evaluate the newest technology applications in the field of production, transport, distribution, storage and use of electric energy.
CEMT-7. Analyse the performance of equipment and facilities in operation to carry out a diagnostic assessment of the use system and establish measures to improve their energy efficiency.
CEMT-5. Employ technical and economic criteria to select the most appropriate thermal equipment for a given application, dimension thermal equipment and facilities, and recognise and evaluate the newest technological applications in the production, transportation, distribution, storage and use of thermal energy.
CEMT-9. Undertake projects related to energy management in production and service sectors, recognise and value advances and developments in the field and contribute innovative ideas.
CEMT-3. Assess the economic, social and environmental impact of the production, use and management of energy, with a holistic view of the life cycle of the different systems, and recognise and value the most remarkable developments in the fields of energy efficiency and the rational use of energy.

Transversal:

CT3. TEAMWORK: Being able to work in an interdisciplinary team, whether as a member or as a leader, with the aim of contributing to projects pragmatically and responsibly and making commitments in view of the resources that are available.
CT4. EFFECTIVE USE OF INFORMATION RESOURCES: Managing the acquisition, structuring, analysis and display of data and information in the chosen area of specialisation and critically assessing the results obtained.

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## Teaching methodology

Teaching methodology:

The course teaching methodologies are as follows:

- Lectures and conferences: presentation of knowledge by lecturers or guest speakers.
- Participatory sessions: collective resolution of exercises, debates and group dynamics, with the lecturer and other students in the classroom; classroom presentation of an activity individually or in small groups.
- Theoretical/practical supervised work (TD): classroom activity carried out individually or in small groups, with the advice and supervision of the teacher.
- Homework assignment of reduced extension: carry out homework of reduced extension, individually or in groups.
- Homework assignment of broad extension: design, planning and implementation of a project or homework of broad extension by a group of students, and writing a report that should include the approach, results and conclusions.
- Evaluation activities (EV).

Training activities:

The course training activities are as follows:

- Face to face activities
o Lectures and conferences: learning based on understanding and synthesizing the knowledge presented by the teacher or by invited speakers.
o Participatory sessions: learning based on participating in the collective resolution of exercises, as well as in discussions and group dynamics, with the lecturer and other students in the classroom.
o Presentations (PS): learning based on presenting in the classroom an activity individually or in small groups.
o Theoretical/practical supervised work (TD): learning based on performing an activity in the classroom, or a theoretical or practical exercise, individually or in small groups, with the advice of the teacher.

- Study activities
o Homework assignment of reduced extension (PR): learning based on applying knowledge and presenting results.
o Homework assignment of broad extension (PA): learning based on applying and extending knowledge.
o Self-study (EA): learning based on studying or expanding the contents of the learning material, individually or in groups, understanding, assimilating, analysing and synthesizing knowledge.

## Learning objectives of the subject

The aim of the course is to introduce advanced methodologies (semi-analytical and numerical) for the analysis and simulation of heat engines, both axial thermal turbomachinery as reciprocating internal combustion engines. Based on a detailed description of the phenomenology of fluid dynamics and heat and mass transfer present, work is mathematical formulation and solution techniques at different levels. All this in the context of this specific thermal systems and their design parameters and operating characteristics.
The course starts with the thermodynamic analysis of gas turbines and steam and thermal systems which are integrated different (with regenerative cycles, a combination of high and low turbine, cogeneration, etc.). The cycle analysis is performed both under design and prediction, considering in both cases the effects of heat loss in the equipment (compressors, turbines, combustion chambers, ducts, etc.) gas at high speeds.
The second part presents the detailed analysis of system components. This level of analysis involves delving into the fluid dynamic and thermal aspects that affect each component. First study the flow behaviour of constant or variable section (nozzles and diffusers) and heat exchangers. The study of the mathematical formulation of the numerical combustion leads to the detailed analysis of constant pressure combustion chambers. Finally, study the flow inside gas turbines and steam and, in the case of gas turbines, axial compressors, entering design aspects of blades and considering aspects such

as its cooling.
The third and last part of the course will be devoted to internal combustion reciprocating engines. Most of the methodology used in the course so far may be used in the calculation and design of engines from a standpoint of fluid dynamics and heat. We will have yet to enter specific aspects such as the loading and unloading process, especially the spread of combustion and flame front in the combustion chamber. We consider Otto cycle cases as well as Diesel cycle cases.

Learning Outcomes:

At the end of the course, the student:
Consolidation basics of heat transfer phenomena and mass (mathematical formulation, analytical and numerical techniques for solving ...) within the framework of a technological application of industrial and social importance such as heat engines.
Consolidation of conventional methods of calculation of this equipment (e.g. triangle of speeds in gas and steam turbines, combustion thermodynamic equilibrium, etc.) and resolution systems from the point of view of design and prediction.
Application of advanced methods of numerical simulation engine (axial and alternative internal combustion) with multidimensional analysis type. Application to the resolution of a combustor first level (unidimenisonal detailed analysis and transient).

## Study load

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|---|---|---|---|
| Total learning time: 125h | Hours small group: | 30h | 24.00% |
| | Guided activities: | 10h | 8.00% |
| | Self study: | 85h | 68.00% |

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## Content

| Content 1. Heat engines and the system in which they are integrated. Global thermodynamic analysis | Learning time: 18h<br>Theory classes: 4h<br>Practical classes: 1h<br>Guided activities: 1h<br>Self study : 12h |
|---|---|

Description:

Introduction to heat engines and identification of the phenomenology of fluid dynamics and heat transfer present. It focuses on the characterisation of gas and steam turbines. It starts with gas turbines and a global analysis of types of the different components of the cycle (analysis based on overall balance of conservation of mass, energy and entropy). The closing of the formulation requires the use of empirical coefficients (isentropic and polytropic performance, heat loss performance, combustion performance, efficiency of heat exchangers, etc.). This poses the case of design as the prediction. The second part presents the cycles with steam turbines and their peculiarities and elements of these systems (steam generators, condensers, pumps, etc.).

Related activities:

Theory class
Practical class
Guided activities

Specific objectives:

General introduction to the course. Analysis of gas turbine cycles. Thermodynamic analysis of the compressor and turbine considering the effects of heat loss, gas flows at high speed and compression and expansion in multi-stages. Analysis of the combustion chamber considering complete combustion in thermodynamic equilibrium and combustion performance. Treatment of heat exchangers (recuperators, intercoolers, etc.) based on semi-analytical methods of e-NTU types.
Calculating the cycle in cases of design, analysing the parameters that characterise the behaviour of the system (e.g. compression ratio, temperature out of the combustion chamber, heat potential to the heat exchanger in the recuperators, etc.) Defining the main parameters of the cycle (cycle performance, specific work, specific consumption, etc.).
Calculating the cycle from the point of view of prediction (this is completely defined cycles where the influence of the variation of the different boundary conditions of the system are evaluated (e.g. fuel flow and air temperature at the entrance of the combustion chamber, air conditions for admission to the compressor, etc.). Methods for solving nonlinear and coupled equations.
Application of the methods mentioned above to the case of steam turbines and their most characteristic elements (steam generators, condensers, pumps, economisers, etc.).

| Content 2. Detailed analysis of auxiliary components of power cycles | Learning time: 17h<br>Theory classes: 2h<br>Practical classes: 2h<br>Guided activities: 1h<br>Self study : 12h |
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Description:

This topic is devoted to the detailed analysis of some of the ancillary components present in the gas and steam turbines. First the gas flow in constant section channels is analysed, considering both the case of low Mach number and the case of compressible flow. The methodology of the resolution considers the heat transfer of the flow with the surrounding environment. The treatment will allow the analysis of heat loss from the pipes outside.
In the second step the analysis of variable section behaviours is performed, specifically nozzles and diffusers.
An immediate application of this methodology is the treatment of heat exchangers with more general and versatile techniques that were indicated in the previous topic (e-NTU method). It will be possible to do both transient and steady cases. Also a third situation corresponding to section geometries and variable volume will be presented: the alternative compressors. This theme will allow the consolidation of the explanations of the flow channels and will be subject to a preparation of five alternative engines (without the complication of representing the combustion). The discretisation of the governing equations (mass, momentum and energy) and its attachment as part of a global resolution algorithm is explained.

Related activities:

Theory class
Practical class
Reduced scope work
Broad scope work

Specific objectives:

Specific objectives:
Analysis of flows inside constant cross section channels. Discretisation of the equations of mass, momentum and energy. Resolution methods of step-by-step types. Case of critical flow and exist of underexpansion. Extension to the study of heat transfer in the walls of the duct and the heat loss to the outside.
Extension of the above analysis to the case of nozzles and diffusers. Possibility of critical flow and presence of shock waves. Case of overexpansion and underexpansion. Cooling nozzles.
Analysis of interesting technological applications in the field of engines. On one hand, the calculation of heat exchangers with advanced techniques to analyse both steady and transient situations. On the other hand, the reciprocating compressors, which present specific phenomenology (flow through valves, heat transfer in the compression chamber, etc.) and the discretisation of equations and their transient resolution with zonal analysis (line suction, suction valve, compression chamber, discharge valve, discharge line). The effects of cooling are considered.

| Content 3. Phenomenology of combustion and analysis of combustion chambers | Learning time: 36h 30m<br>Theory classes: 5h<br>Practical classes: 4h 30m<br>Guided activities: 3h<br>Self study : 24h |
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Description:

The first topic of this course is the treatment of combustion chambers through complete combustion in thermodynamic equilibrium with an empirical coefficient, combustion performance, which is about ideal to real treatment.
This type of analysis is not suitable for studying the effect of bypass flows for cooling the combustion gases, the study of the influence of geometry, the lighting, the formation of NOx, etc.
Thus, a second level of analysis will be the considerationof incomplete combustion in thermodynamic equilibrium (selection of equilibrium reactions, thermodynamic evaluation of the equilibrium constants Kp, solving systems of nonlinear equations). From there, the mathematical treatment of the combustion in its entirety is shown: mass diffusion in gas mixture, transport equations and laws of the constituent chemical species (especially Fick law), conservation equations of momentum and energy (for mixtures with chemical reactions), chemical kinetics (evaluation of the terms of the generation/destruction of species in the equations of the species). Different reaction mechanisms and evaluation of kinetic constants (Arrhenius law) are presented.
Finally, in the case of gas turbine combustors, an advanced analysis of one-dimensional transient types will be presented that allow students a first approach detailed in this equipment.

Related activities:

Theory class
Practical class
Reduced scope work
Broad scope work

Specific objectives:

Analysis of incomplete combustion in thermodynamic equilibrium. Possible proposals of reaction products and reaction equations. Evaluation of equilibrium constants Kp and Kc. Methods for solving systems of nonlinear equations (Newton type methods).
Mathematical formulation of combustion. Gas mixture flow: mass diffusion phenomena, species transport equation, constitutive laws for mass flow diffusion (Fick law, Soret effect, Duffour effect). Generalisation of momentum equation and the equation of energy flows with chemical reactions. Chemical kinetics: elementary reactions and reaction mechanisms, evaluation of kinetic constants directly (Arrhenius law) and reverse ratio evaluation of production/destruction of species per unit volume and time. Integral-differential equation of radiation and problem resolution in reactive gases. Turbulent combustion: possibilities and limitations of different levels of modelling (RANS, LES, DNS). Introduction to the numerical resolution of governing equations: discretisation of generic equations of convection-diffusion and global algorithms of resolution based on the pressure (implicit rate SIMPLEC). Examples of resolution and phenomenological aspects.
Finally, after the presentation of general mathematical formulation of reactive flows, a perfectly approachable case will be posed to the student with a reasonable time and without the need for large computing requirements. It is a combustor with one-dimensional transient analysis. In this case the methodologies of treatment of convection from topic 2 (section to section) will not be used, since the effects of mass and energy diffusion are important (the equations are elliptical in nature). The treatment will be more generally applied methodology of discretisation of the equations already presented and with techniques of coupled equations of SIMPLEC type. In the case of liquid fuel, transport models will be discussed and evaporation of the droplets.

| Content 4. Axial turbomachinery: gas turbines and vapour | Learning time: 26h<br>Theory classes: 3h<br>Practical classes: 2h<br>Guided activities: 3h<br>Self study : 18h |
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Description:
This topic will perform the analysis of the compressor and turbine elements in detail. The level of the study of this content allows the design and analysis of the mechanical characteristics of both turbomachinery from a fluid-thermal study, characterising the fluid by triangles of speeds and conditions of stagnation. This will allow students to characterise geometrically the blades (angles of attack and departure), rotational speed and power extracted from the turbomachinery. Issues related to the cooling of the blades are considered.

Related activities:
Theory class
Practical class
Reduced scope work
Broad scope work

Specific objectives:
Description of the behaviour of fluid through the compressor and the turbine using the triangle of speeds and conditions of stagnation.
Characterisation and calculation of the profiles of the blades. Cooling of the blades.
Characterisation of the operation of turbomachinery and calculation by the degree of reaction, the load factor, flow coefficient and the specific work.

| Content 5. Alternative engines of internal combustion | Learning time: 27h 30m<br>Theory classes: 4h<br>Practical classes: 2h 30m<br>Guided activities: 2h<br>Self study : 19h |
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Description:

This topic will detail the basic phenomenologies of fluid dynamics and heat transfer that characterise the operation of the internal combustion engine, in its two main variants, the engine ignition (Otto engine) and engine power compression (diesel engine). Treatment will focus on the engine block and other system components (carburation, injection, radiator, etc.). Then the combustion process and its effects are described. The ignition of the mixture, both spark and compression are analysed, studying their energy intake needed and the conditions that must be realised, and autoignition time. The analysis will be completed by analysing the propagation of flame in front of the camera, detailing the combustion process and characterised by the speed of flame. The methodology to address cases where the front of the flame is in lamellar terms will be described and concepts will be provided to study turbulent cases.
Finally, the aspects not directly related to the combustion process and extraction work, such as engine cooling and an input and extraction of gases in the cylinder are analysed.

Related activities:

Theory class
Practical class
Reduced scope work
Broad scope work

Specific objectives:

Identification of basic phenomenologies of fluid dynamics and heat transfer in engine ignition and compression ignition.
Study of factors that enable the ignition of a mixture inside a chamber.
Characterisation of the spread of the front of the flame under laminar or turbulent conditions. Details on the effects of turbulence on the propagation, mixing and heat transfer.
Calculation of the spead of propagation of the front of the flame in a premix.
Global analysis considering admission and discharge gas, along with the process of compression and expansion and the effects of engine cooling.

## Planning of activities

| Theory classes | Hours: 30h<br>Self study: 10h<br>Theory classes: 20h |
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Description:
Methodology in large group. The content of the course will follow a model of exhibition class and participation. The material is organised into different groups according to the content areas of knowledge of the subject.

Support materials:
Recommended references. Notes from the professor (copy and/or ATENEA).

Descriptions of the assignments due and their relation to the assessment:
This activity is evaluated in conjunction with the second activity (problems) through coursework and testing knowledge.

Specific objectives:
At the end of this activity, students should be able to master the knowledge, consolidate them and apply them correctly to various technical problems. Moreover, being a techno-scientific subject, the lectures should serve as a basis for the development of other more technical subjects related to the field of heat, such as refrigeration, or Solar Thermal Engines.

| Practical classes | Hours: 30h<br>Self study: 10h<br>Practical classes: 20h |
|---|---|

Description:
Methodology in large group and medium group, as long as the availability of the professor permits it. On each topic there will be some problems in the classroom so that students acquire the necessary guidelines to carry out this resolution: simplifying assumptions, approach, numerical resolution, discussion of results.

Support materials:
Recommended references. Notes from the professor (copy and/or ATENEA).

Descriptions of the assignments due and their relation to the assessment:
This activity is evaluated in conjunction with the first activity (theory) through coursework and exams.

Specific objectives:
At the end of this activity, students should be able to apply theoretical knowledge to solve different types of problems. Given the methodology, students should be able to:
1.- Understand the statement and analyse the problem.
2.- Propose and develop a scheme of the same resolution.
3.- Solve the problem using proposed equations with a suitable algorithm resolution.
4.- Critically interpret the results.

| Guided activities | Hours: 28h<br>Guided activities: 8h<br>Self study: 20h |
|---|---|

Description:
Students must perform guided activities. The activities consist in solving small problems, of whcih the data may be the result of a laboratory experiment or proposed data by the professor. The structure to be followed:
- Preparation of the activity by a manual of practice.
- Groups of 2 or 3 people with a maximum duration of two hours.
- Discussion of the results obtained and the problems that have arisen during the course of practice.
- Completion of a report on the practice carried out with results, questions and conclusions. This report will be evaluated together with the completion of the practice.

Support materials:
Recommended references. Notes from the professor (copy and/or ATENEA).

Descriptions of the assignments due and their relation to the assessment:
Reports should follow guidelines given in class.

Specific objectives:
Consolidate the knowledge acquired in theory classes and practices.

| Written test | Hours: 2h<br>Guided activities: 2h |
|---|---|

Description:
Development of a written test of the course contents 1 and 2. It includes theoretical aspects and development problems.

Support materials:
Recommended references. Notes from the professor (copy and/or ATENEA).

Descriptions of the assignments due and their relation to the assessment:
The exam will be held freely and the statement delivered along with the statement duly filled in with the data required.

Specific objectives:
Demonstrate the level of knowledge achieved in theoretical activities and problems.

## Qualification system

To review the knowledge acquired by the students, two exams will be carried out: a midterm exam and a final one.

The midterm exam accounts for a 30% of the final mark. The final exams accounts for a 40%.

Apart from that, a lab work is proposed and accounts for at least a 30% of the final mark.

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## Bibliography

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### Complementary:

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The Jet engine. London: Rolls-Royce, 2005. ISBN 9781119065999.

Others resources:

Audiovisual material

Transparencies, proposed problems to be used in class

Resource

Notes made by the professor of the course

Resource