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220222 - Thermal Turbomachinery and Combustion

Coordinating unit: 205 - ESEIAAT - Terrassa School of Industrial, Aerospace and Audiovisual Engineering
Teaching unit: 724 - MMT - Department of Heat Engines
Academic year: 2019
Degree: MASTER'S DEGREE IN SPACE AND AERONAUTICAL ENGINEERING (Syllabus 2016). (Teaching unit Optional)
MASTER'S DEGREE IN INDUSTRIAL ENGINEERING (Syllabus 2013). (Teaching unit Optional)
MASTER'S DEGREE IN AERONAUTICAL ENGINEERING (Syllabus 2014). (Teaching unit Optional)
ECTS credits: 3 Teaching languages: English

Teaching staff

Coordinator: Carlos David Pérez Segarra

Others: Assensi Oliva
Jorge Chiva

Opening hours

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

Teaching methodology

The course is divided into a fundamental/basic part and an optional part. All the students have to carry out the basic part which consists of both theoretical and practical lectures. In the theory lectures, lecturers will introduce the theoretical basis of the concepts, together with the methodology and main results, using examples to facilitate the students' understanding.

Practical lectures will be carried out to consolidate the basic concepts and to introduce the students in the analysis of these thermal systems. Lectures will encourage the students to do their own computer programs not only to solve the proposed exercises, but also to use the code to carry out parametric studies as if it were a virtual experimental set up. Most of this practical work will be done by the students out of the lecture room, as self-study.

Five optional activities, which are indicated in the program of the subject, will be offered to all the students. These extra activities will be scheduled out of the standard lectures timetable. Each activity will last approximately 3 h. The students must follow at least one of the optional activities offered during the course.

Apart from the recommended bibliography, tutorials developed by the lectures (this material is uploaded in Atenea during the course) will also be used.

Learning objectives of the subject

The objective of the course is to show basic and advanced methodologies (semi-analytic and numerical methods) for the simulation of thermal turbomachinery, specifically gas and vapour turbines. After a detailed description of the characteristics of the thermal and fluid dynamic phenomena of these machines, the mathematical formulation is presented together with different techniques to solve the equations, from relatively simple analysis based on semi-analytic methods to advanced analysis based on the numerical resolution of the equations. All this in the framework of these specific thermal systems and considering their characteristic parameters and working conditions.

The course starts with a thermodynamic analysis of gas turbines which basically consists of a compressor, a combustion chamber, and a turbine. More complex systems are also considered (cycles with intercoolers, regenerators, reheat combustors, multiple compressors and/or combustion chambers and/or turbines, cogeneration cycles, etc.). The study of the cycle is carried out considering the design approach (the components of the cycle have to be calculated under specified conditions), but also considering the more difficult prediction approach (the behaviour of a well-defined cycle components is evaluated under out of design conditions). Special topics related to heat transfer losses, pressure losses, gases at high velocities, etc., are also taken into account.

A similar analysis is carried out for vapour turbines, which basically consists of a steam generator (usually a steam boiler furnace), a vapour turbine, a condenser and a pump.

The second part of the course focusses the attention on the detailed analysis of the components. This approach needs a higher knowledge of the thermal and fluid dynamics issues present in these systems. Firstly, the analysis of the flow in ducts of constant and variable cross-sectional area (as nozzles and diffusers) is carried out. After that, the analysis of heat exchangers (i.e. regenerators and intercoolers in gas turbines, or steam generators and condensers in vapour turbines) is presented. The study of the basic principles of combustion processes allows the analysis of combustion chambers at constant pressure. Finally, axial compressors and turbines are studied considering the design of their blades taking into account not only aerodynamic issues, but also cooling techniques.

Some of the activities above detailed will be optional. These activities are explained in the syllabus of the subject (see modules 2, 3 and 4). The student will be encouraged to follow at least one of these extra activities.

Objectives of the learning process:
1.- Consolidation of the fundamental knowledge on thermal and fluid dynamic phenomena present in turbomachinery and combustion: mathematical formulation, semi-analytic and numerical resolution techniques, working parameters under different technical applications, etc.
2.- Consolidation of standard methods of analysis of these systems considering both design and prediction approaches, and also their components (e.g. velocity triangles in gas and vapour turbines, F-factor and e-NTU methodologies for the analysis of heat exchangers, combustion under thermodynamic equilibrium conditions, etc.).
3.- Application of advanced methodologies for the numerical resolution of the components (turbines, compressors, heat exchangers, etc.) using multidimensional approaches. Regarding the combustion chamber, an unsteady and one-dimensional analysis will be presented considering finite-rate chemical reactions. This part of advanced methodologies will be offered as extra activities.

Study load

Total learning time: 75h	Hours large group:	27h	36.00%
	Self study:	48h	64.00%

Content

Module 1: Gas and steam turbines. Thermodynamic analysis and semi-analytic models	Learning time: 16h Theory classes: 6h Self study : 10h

Description:

Introduction to gas and steam turbines. Identification of the thermal and fluid dynamics phenomena which condition the behaviour of these systems. The first part of this lecture starts with a thermodynamic analysis of gas turbines. The elements of the cycle are analysed considering global balances of mass, energy and entropy. Some empirical coefficients are needed to close the formulation, i.e. the isentropic and polytropic efficiencies, heat transfer losses coefficient and the combustion efficiency. The different heat exchangers (regenerators and intercoolers) are analysed using semi-analytic models.

The second part of the lecture deals with vapour turbines. An analogous presentation of the first part will be given considering the specific features of these systems (steam generator, condenser, pumps, complex systems, etc.).

Optional activity 1: The cycle is solved considering not only the design approach (the basic one in this course), but also the more difficult prediction approach.

Related activities:

- General introduction to the subject. Analysis of different gas turbine cycles. Thermodynamic study of the compressor and the turbine considering arbitrary gas velocities (low and high Mach numbers), isentropic efficiencies, heat losses, and multi-stage compressor and expansion processes. Study of the combustion chamber considering complete combustion with excess air and thermodynamic equilibrium. Real conditions are described using the efficiency of the combustion. Analysis of heat exchangers (regenerators and intercoolers) using semi-analytic methods (F-factor and e-NTU).

- Cycle resolution in design approach (components are calculated under specified working conditions). Evaluation of the parameters which characterized the cycle, e.g. compression ratio, outlet temperature of the combustion chamber, heat power to be exchanged in the regenerators, etc. Definition of the main cycle parameters: efficiency of the cycle, specific work, specific consumption, etc.

- Application of the explained methodologies to vapour turbines and their main components: turbine, steam generator, condensers, pumps, economizers, heaters, de-aerators, etc.

- For optional activity 1: Cycle resolution in prediction approach. In this case the cycle components are completely defined and the objective is the evaluation of cycle conditions under specified boundary conditions (e.g. influence of fuel mass flow rate consumption, inlet air temperature in the compressor, etc.). Evaluation of non-linear set of equations.

Module 2: Detailed analysis of some ancillary components (ducts, nozzles, diffusers) and heat exchangers of these power cycles	Learning time: 18h Theory classes: 6h Self study : 12h

Description:

This lesson is dedicated to some ancillary (auxiliary) components present in gas and vapour turbines. Firstly, the flow of gases in channels of constant cross-sectional area are analysed considering any velocity (from low to high Mach numbers). The methodology of analysis will take into account heat transfer losses to the ambient. As a second step, the methodology will be extended to nozzles and diffusers, where the cross-sectional area of the flow is not constant.

Apart from the flow in channels of constant or variable cross-section, the methodology can be easily extended to the analysis of heat exchangers. The technique is much more powerful than the semi-analytical methods (F-factor or e-NTU) presented in the previous lesson, allowing the analysis of steady or unsteady situations, non-uniform heat transfer coefficients, etc.

Related activities:

- Detailed analysis of flows of liquids in channels of constant cross-sectional area. Discretization of the conservation equations (mass, momentum and energy). Step-by-step algorithm. Extension to gas flows at any velocity (low and high Mach numbers). Analysis of exit conditions under critic and under-expanded flow conditions. Conjugated heat transfer analysis: flow inside the duct and the duct itself considering heat transfer losses to the ambient.

- Extension of the previous analysis to ducts of variable cross-sectional area, i.e. converging and diverging nozzles and diffusers. Shock waves. Analysis of under-expanded and over-expanded nozzles. Cooling effects in nozzles and diffusers.

- Application of these methodologies to the design of heat exchangers: advanced analysis. Analysis of steady and unsteady situations. Comparison with experimental data.

Module 3: Fundamentals of combustion phenomena. Detailed analysis of combustors	Learning time: 21h Theory classes: 8h Self study : 13h

Description:

In the lesson, combustion phenomena is firstly analysed considering complete combustion under thermodynamic equilibrium conditions. An empirical coefficient, the combustion efficiency, is used to relate the ideal behaviour with the real one. This kind of analysis is not adequate for the analysis of incomplete combustion out of equilibrium conditions, NOx formation, ignition, etc.

Therefore, a second level of analysis deals with incomplete combustion, but still under equilibrium conditions. This requires the selection of equilibrium reactions, the evaluation of their equilibrium constants, and the resolution of non-linear set of algebraic equations.

Optional activity 2: From here on, a more advanced analysis will be presented based on a general analysis of the combustion phenomena: mass diffusion of gas mixtures, transport equations of the chemical species and their constitutive laws (specially Fick's law), transport equations for momentum and energy (gas mixtures under chemical reactions), chemical kinetics for the evaluations of the source/sink terms in the species equations. Different reaction mechanisms are presented together with the evaluation of their kinetic constants (Arrhenius' law).

Optional activity 3: Finally, and for gas turbines, a detailed steady and unsteady one-dimensional analysis of a combustor is presented. The analysis is based on the resolution of the governing equations taking into account finite chemistry. The student will be able to simulate a real combustor with a reasonable effort.

Related activities:

- Fundamentals of combustion phenomena. Analysis of incomplete combustion under thermodynamic equilibrium conditions: selection of the combustion products and equilibrium reactions. Evaluation of the equilibrium constants Kp and Kc. Algorithms for solving non-linear set of equations (Newton like methodologies).

- For optional activity 2: Mathematical analysis of combustion phenomena. Flow in gas mixtures: mass diffusion, transport equation for the species, constitutive laws of mass diffusion (Fick's law, Soret effect, Duffour effect). Generalization of the momentum and energy equations for reactive flows. Reaction rates - chemical kinetics: elementary reactions and reaction mechanisms, evaluation of the forward and backward chemical constants (Arrhenius's law), evaluation of the production/destruction rates of the species. Radiative transport equation and reactive gas flows. Turbulent combustion: possibilities and limitations of different levels of analysis (RANS, LES, DNS). Introduction to the numerical resolution of the governing equations: discretization of the generic convection-diffusion equation. Segregated algorithm for coupling the governing equations (SIMPLEC like). Examples of different applied reactive flows and analysis of phenomenological aspects and experimental results.

- For optional activity 3: After the presentation of the general methodology of modelling and analysis of reactive flows, an applied case of technological interest will be studied: one-dimensional analysis of a combustor considering steady or unsteady processes. This case involves the main issues of combustion phenomena but its resolution can be afforded by the students with a reasonable effort. The step-by-step method described in Unit 2 is not applied here because the mass and energy diffusion effects give the equations an elliptic structure. Instead, the SIMPLEC approach described above is applied. In case of liquid fuel, models of the liquid drop transport and evaporation are also described.

Module 4: Axial compressors and gas and vapour turbines	Learning time: 20h Theory classes: 7h Self study : 13h

Description:

A detailed analysis of axial compressors and gas and vapour turbines is presented. Two levels of analysis are shown. The first one allows the analysis and design of the mechanical characteristics of these turbomachines (axial compressors and turbines) using the velocity triangles and stagnation conditions. In this way, the student will be able to characterize geometrically the blades (leading and trailing edge angles), rotational speed, power delivered or extracted from the turbomachine. Issues related to blade cooling are also discussed.

Optional activity 4: The second level of analysis involves the detailed resolution of the flow through the rotating blades using the Navier-Stokes equations (computational fluid dynamics and heat transfer approach). The objective is to give the students a general picture of the most advanced analysis of aerodynamics issues in turbomachines. Some important topics are turbulence modelling and numerical techniques to solve the governing equations. Different illustrative results will be presented.

Related activities:

- Detailed description of the flow behaviour through the different stages of compressors or turbines is described by means of the triangle of velocities and the stagnation conditions.

- Characterization and evaluation of the blade profiles. Gas turbine blade cooling.

- Characterization of the working conditions of these turbomachines. Analysis based on the degree of reaction, the discharged coefficient, the flow coefficient and the specific work.

- For optional activity 4: Advanced analysis of turbomachines. Examples of detailed modelling of the flow through axial compressors and turbines.

Qualification system

- partial exam: 20%;
- Final exam: 35%;
- Lab work: 45%.

Bibliography

Basic:

Bergman, T. [et al.]. Fundamentals of heat and mass transfer. 7th ed. Hoboken, NJ: Wiley & Sons, 2011. ISBN 9780470501979.

Eckert, E. R. G.; Drake, R. Analysis of heat and mass transfer. Washington: Hemisphere Pub. Corp, cop. 1972. ISBN 0891165533.

Warnatz, J.; Maas, U.; Dibble, R. W. Combustion: physical and chemical fundamentals, modelling and simulation, experiments, pollutant formation. 4th ed. Berlin [etc.]: Springer-Verlag, 2006. ISBN 9783540259923.

Saravanamuttoo, H. I. H.; Rogers, G.; Cohen, H. Gas Turbine Theory. 5th ed. Harlow, England ; New York: Prentice Hall, cop. 2001. ISBN 013015847X.

Ferguson, Colin R.; Kirkpatrick, A. T. Internal combustion engines : applied thermosciences. 2nd ed. New York [etc.]: John Wiley & Sons, cop. 2001. ISBN 0471356174.

Patankar, Suhas V. Numerical heat transfer and fluid flow. Washington : Hemisphere ; New York: McGraw-Hill, cop. 1980. ISBN 0070487405.

Professors of the subject. Specific material developed by the lecturers of the subject (slides, reports, problems to be solved in class, etc.).

Complementary:

Ferziger, J. H.; Peric, M. Computational methods for fluid dynamics. 3rd ed. Berlin [etc.]: Springer, 2002. ISBN 3540420746.

Pope, S. B. Turbulent flows. Cambridge [etc.]: Cambridge University Press, 2000. ISBN 0521591252.

Shapiro, Ascher H. The dynamics and thermodynamics of compressible fluid flow. New York: The Ronald Press Company, 1954.

Turns, Stephen R. An introduction to combustion: concepts and applications. Boston [etc.]: McGraw-Hill, 2006. ISBN 9780071260725.

Kuo, Kenneth K. Principles of combustion. 2nd ed. New York: John Wiley & Sons, cop. 2005. ISBN 0471046892.

Williams, F. A. Combustion theory: the fundamental theory of chemically reacting flow systems. Menlo Park, Calif: Benjamin/Cummings, cop. 1985. ISBN 0805398015.

Poinsot, Thierry; Veynante, Denis. Theoretical and numerical combustion. 2nd ed. Philadelphia: Edwards, 2005. ISBN 1930217102.

Lecuona Neumann, A.; Nogueira Goriba, J. I. Turbomáquinas : procesos, análisis y tecnología. Barcelona: Ariel, 2000. ISBN 8434480298.

Mataix, Claudio. Turbomáquinas térmicas: turbinas de vapor, turbinas de gas, turbocompresores. 3ª ed. Madrid: Dossat 2000, 1988. ISBN 842370727X.

Lakshminarayana, Budugur. Fluid dynamics and heat transfer of turbomachinery. New York [etc.]: John Wiley & Sons, cop. 1996. ISBN 0471855464.

Cumpsty, N.A. Jet propulsion : a simple guide to the aerodynamic and thermodynamic design and performance of jet engines. 2nd ed. New York: Cambridge Univeristy Press, 2003. ISBN 0521541441.