Master 2 Thermal Science & Energy Syllabus

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1 Fundamentals of heat transfer [8 ECTS]

1.1 Engineering heat transfer (EHT)

Objectives: The objectives of this first course in heat transfer is: (i) to introduce the fundamentals of this subject; (ii) to establish the relationship of these origins to the behavior of thermal systems. It should develop methodologies which facilitate application of the subject to a broad range of practical problems and it should give necessary tools to perform engineering analysis providing useful information concerning the design and/or performance of a system or process.

Contents: ▷ Introduction. ▷ Conduction: one-D steady-state conduction; transient conduction. ▷ Convection: usual concepts and relationships (correlations): external flow; internal flow; free convection. ▷ Radiation: processes and properties; exchange between surfaces.

A. Gueled (18 h TD – 1.5 h Ctrl)

1.2 Physics of heat transfer (PHT)

Objectives: The objectives of this course e are: (i) to show the physical basis of the laws governing heat transfer in solids and fluids (ii) to develop microscopic analysis (up to the particle scale) of the different heat transfer mode (iii) to present a synthesis on the various analytical solutions of heat transfer equation.

Contents: ▷ Introduction (mean free path and relaxation time). ▷ Elementary interpretation of heat transfer using gas. ▷ Conduction: fundamental physical basis. ▷ Convection: fundamental physical basis. ▷ Radiation: fundamental concepts and properties. ▷ Synthesis on analytical solutions for heat transfer equation.

B. Garnier *&* G. Fugallo (18 h TD – 1.5 h Ctrl)

1.3 Convective heat transfer (CHT)

Objectives: This course is designed based on the axiom that the engineering student should learn to reason from first principals to avoid being at loss when faced by new a problem. It aims at giving in depth and easily usable knowledge of convective heat transfer at graduate level. It is assumed that the student has a typical undergraduate background in applied thermodynamics, fluid mechanics and heat transfer.

Contents: ▷ Introduction. ▷ The differential equations of the turbulent boundary layer: instantaneous equations of turbulence; Reynolds decomposition; time-averaged equations and turbulence statistics; Reynolds-averaged equations of turbulence; mechanical energy transport equation; turbulence kinetic energy transport equation; k-equation for the turbulent boundary layer equation; dissipation transport equation. ▷ Momentum transfer in turbulent boundary layer. ▷ Heat transfer in turbulent boundary layer. ▷ Momentum transfer in turbulent flow in pipes. ▷ Heat transfer in turbulent flow in pipes.

A. Gueled *&* J. Bellettre (21 h TD – 1.5 h Ctrl)

1.4 Radiative heat transfer (RHT)

Objectives: The objectives of the radiative heat transfer course are: (i) to introduce the fundamental basis governing the exchange of energy with thermal radiation; (ii) to make the link between the optical thickness and the properties of a given material; (iii) to analysis the radiative exchanges in solid participating media (iii) to understand absorption and scattering by particles, fibers, and agglomerates

Contents: ▷ Introduction (spectral intensity, black body, properties at interfaces, properties at volumes). ▷ Mean penetration distance for different families of material (polymer, ceramic, metal,...). ▷ Radiative Transfer Equation. ▷ Solution of the Radiative Transfer Equation in Participating Media. ▷ Mie scattering theory.

B. Rousseau (9 h TD – 1.5 h Ctrl)

2 Experimental and numerical methods [8 ECTS]

2.1 Experimental methods (EM)

Objectives: The objective of this course is to initiate students about the different physical phenomena and frequently encountered errors in the measurement of temperature, heat flux and the velocityfield, pressure and concentration in fluid flow. In each case the classical tools of measurement processing will be mentioned with the values and characteristics obtained and the constraints imposed on the signal processing quality.

Contents: An overview of different techniques of measurement of the velocity in the isothermal and non-isothermal flows (hot wire, hot film, LDV, PIV) will be provided with an emphasis on the physical principle of the measurement to promote the choice of method and understanding of the uncertainties induced. Most useful visualization methods in fluid flow will also be addressed by going from tracking of tracer in interferometry via shadowgraph methods. The use of these techniques to obtain the temperature field or pollutant concentration will be discussed as well as in situ measurements to obtain the composition or density of the fluid. We also present the thermometric thermometry phenomena used in contact and contactless configuration (thermoelectric effect, electrical resistance heat, pyrometry and infrared imaging), methods of manufacture of sensors (including thermocouples), the errors due to on the one hand the physical phenomenon (inaccuracy on measuring the size, parasitic effects…) and on the other hand to the disruption of local temperature field (analysis and modeling errors). Finally, we recall the different methods of measuring heat flux (flux sensors or enthalpy gradient or power dissipation, microcalorimetry, inverse method) and the main techniques for measuring thermophysical properties of materials.

B. Garnier & A. Gueled (15 h TD – 20 h TP)

2.2 Numerical methods (NM)

Objectives: The objective of this course in numerical methods is to give some basic theoretical bases along with some practice skills for heat transfer modeling. The course shall begin with an introduction to potential applications with the usual related pitfalls. The major tools for solving linear matrix systems and differential equations and systems shall be presented, along with the necessary compromise between accuracy and time consumption. We will then go more deeply to the general method of finite differences, and then specially to the finite elements. We will emphasize on the relations between discretization and solution errors. All theoretical notions will be completed with basic practical applications during tutorials, on the open source environment FreeFEM.

Contents: ▷ Introduction. ▷ Matrix systems and differential systems: Direct and iterative methods for solving matrix systems; Euler, Runge-kutta, SSOR and conjugate gradients methods for differential systems. ▷ Space approximation for partial differential equations: Finite differences methods; Finite elements methods. ▷ Application on fluid flows, acoustic or heat transfers.

Y. Favennec (15 h TD – 1.5 h Ctrl)

2.3 Inverse problems **(IP)**

Objectives: The objective of this course in numerical methods is to give some basic theoretical bases along with some practice skills for inverse heat transfer. The course shall begin with an introduction to inverse problems and the main differences with the so-called direct problems. It will be shown that solving inverse problems may enhance the quality of direct problems after recovering lacking data. Different optimization methods (deterministic, stochastic) will be presented, but gradient-type methods shall be more deeply studied. It will be shown how regularization tools may enhance the quality of the solution, since the inverse problems are likely to be ill-posed. Different regularization methods will be presented according to specific cases. The whole theory will be applied on a relatively simple academic example, for which the numerical modeling has been developed in the previous course (numerical methods).

Contents: ▷ General ideas. ▷ Cost function definitions. ▷ Optimization methods. ▷ Ill-posed problems and regularization. ▷ Applications.

Remark: common course with TE5 (ctmf)

Y. Favennec (9 h CM – 8 h Proj)

3 Fluid mechanics **[5 ECTS]**

3.1 Fundamentals **(FFM)**

Objectives: The objectives of this first course is to give an introduction to fluid dynamics. First, we will develop the concept of control volume. Then we will establish the differential equations of conservation. Some solutions of these equations will be developed for simple internal and external flows. It should give the background required by more advanced courses in fluid mechanics and convective heat transfer.

Contents: ▷ Introduction. ▷ Integral approach: Reynolds transport theorem; conservation of mass; momentum equation; energy equation; Bernouilli equation. ▷ Differential approach: equation of mass conservation; equation of momentum; boundary layer; internal flows.

P. Dupont (12 h TD – 1.5 h Ctrl)

3.2 Turbulence and turbulent flow **(TTF)**

Objectives: This course gives a solid background in the subject of turbulence, developing both physical insight and the mathematical framework needed to express the theory. The course begins with a review of the physical nature of turbulence, statistical tools, and space and time scales of turbulence. Then the basic theory is presented, illustrated by examples of simple flows and developed through wall bounded turbulent flows.

Contents: ▷ The nature of turbulent motion. ▷ Statistical description of turbulent motion. ▷ Turbulence equations. ▷ Interpretation of correlations. ▷ Spectra eddies in turbulence. ▷ Homogeneous and isotropic turbulence. ▷ Dynamical processes of the energy cascade. ▷ Reynolds number similarity and self-preservation. ▷ Turbulent motion near a wall.

M. Visonneau (12 h CM – 1.5 h Ctrl)

3.3 Hydrodynamic stability and dynamical systems (HSDS)

Objectives: After a short description of the notion of stability, we choose the Rayleigh-Bnard thermoconvective stability as an example on which we develope the linear theory of stability. In the second part of the course, the notion of dynamical systems is introduces and theoretical tools for characterization of these systems are developed. We then proceed to the notion of chaos and use again the Rayleigh-Bnard thermoconvective system to develop the Lorenz model, which we study in details to introduce the notion of strange attractor and scenarios of transition to turbulence.

Contents: ▷ Notion of hydrodynamic stability. ▷ The Bénard problem. ▷ The nature of the physical problem. ▷ The basic hydrodynamic equations. ▷ The Boussinesq approximation. ▷ The perturbation equations ▷ The analysis into normal modes. ▷ The equations of marginal state. ▷ The cell patterns. ▷ Phenomenology of chaos. ▷ Theory of nonlinear dynamics and chaos. ▷ Three-dimensional state space and chaos. ▷ Measures of chaos. ▷ Lorenz model.

A. Valance (15 h TD – 1.5 h Ctrl)

4 Heat transfer in solids and heterogeneous media [6 ECTS]

4.1 Heat transfer at interfaces (HTI)

Objectives: This course concerns the heat transfers at solid-solid interfaces, knowing that the contact can be static, dynamic or mobile (sliding, rolling or intermittent). The thermal boundary condition at solid-solid imperfect contact is of the third kind and the coefficient which relates the thermal gradient to the temperature at the interface is the thermal contact resistance. Moreover, when the interface is seat of heat generation, this boundary condition becomes inhomogeneous and the non-homogeneity is the product of the generated heat flux by a coefficient representing the share of the dissipation between the two faces in contact. The goal of this course is to present theoretical approaches which allow describing each one of the two parameters. These approaches are founded on three disciplines: the surfaces topography (rough surfaces), contact mechanics and heat transfers. The basic phenomena relative to each type of interface of contact are approached. We evoke successively the static, dynamic and moving contacts. The thermo-mechanical couplings specific to each type are underlined.

Contents: ▷ Introduction. ▷ The thermal boundary condition at solid-solid contact: the need for modeling. ▷ Surface topography. ▷ Elements of mechanical contacts. ▷ Modeling rough contacts. ▷ The thermal problem: basic phenomena. ▷ Thermal constriction phenomena: Analytical study of the constriction function. ▷ Moving thermal contacts. ▷ Conclusions.

Remark: common course with TE5 (ctmf)

B. Bourouga (12 h TD – 1.5 h Ctrl)

4.2 Heat transfer during composite injection (INJ)

Objectives: he goal of this course is to study two techniques of thermoset composites moulding: Resin Transfer Moulding Process (RTM) and Bulk Moulding Compound process (BMC). The coupled physical phenomena involved with these processes are presented and modelled.

Contents: The RTM process: Presentation of the process technology, Analysis of heat transfer part/tool, Modelling of the filling of the part; Modelling of the curing of the part Simulation issues The BMC processThe BMC material and the features of its components Analysis and interpretation applied to a specific part: pressure, temperature, heat flux. Simulation issues.

V. Sobotka *&* N. Boyard (25.5 h TD – 1.5 h Ctrl)

4.3 Thermophysical properties of polymers (TPP)

Objectives: This course aims to introduce the thermo-physical properties and solidification kinetics of polymers, which are required to calculate heat transfer during polymer and composite part processing, taking into account coupled phenomena.

Contents: ▷ Presentation of the differential scanning calorimetry (DSC), interpretation of signals and determination of specific heat, glass transition, phase change enthalpy; ▷ crystallization kinetics of semi-crystalline polymers: definition of crystallization and the associated micro-structure, mechanism, modeling according to process conditions; ▷ specific volume and thermal conductivity: definition, experimental devices and focus on the importance of the chosen protocol, modeling of these properties.

Remark: common course with Mat5

N. Boyard (15 h TD – 1.5 h Ctrl)

5 Energy systems [3 ECTS]

5.1 Thermal energy storage (TES)

Objectives: This course will teach the basics of TES, future potential of TES and different applications of TES in modern world. Specifically, it will describe what TES is, different forms of TES (sensible, latent, thermochemical), basic principles of each TES technology and how a TES system works for a certain application. The reasons why TES is needed to make new renewable generation sources (i.e. wind, solar) more viable & flexible will be also addressed.

Contents: ▷ Overview on TES technologies/systems; ▷ TES by sensible heat for building applications (low temperature); ▷ Basic knowledge on melting or solidication of PCMs with coupled heat transfer; ▷ TES by latent heat for industrial wasteheat recovery (low/medium temperature); ▷ Basic knowledge on thermochemical storage and their applications in solar power plants (high temperature); ▷ discussion on selected topics for mordern TES applications.

Y. Fan (15 h TD – 1.5 h Ctrl)

5.2 Optimization of energy systems (ESO)

Objectives: Both energy and exergy analyses are undertaken to investigate advanced thermodynamic cycles. Cases studies including optimization approaches are considered for combined heat and power systems, combined gas-vapor power systems, multi-level temperature refrigeration systems and absorption refrigeration systems.

Contents:

Remark: common course with TE5 (ese)

B. Auvity, C. Josset, Y. Favennec (24 h TD – 1.5 h Ctrl)

6 Internship [30 ECTS]

6.1 Internship (INTERN)

Objectives: Practice of theoretical notions and discover research.

Contents: ▷ The second semester is dedicated to an internship in either an academic laboratory, or within and R & D department of a company.

(5 months)