# Content and Minimum Learning Outcomes for the Course of Single- and Two Phase Thermal-hydraulics

***W. Ambrosini***

<table>
<tr><th colspan="3">Course on “Single and Two-Phase Thermal-hydraulics”</th></tr>
<tr><th>Units and LO Statements</th><th colspan="2"></th></tr>
<tr><td rowspan="3">Unit 1 – Fluids and Balance Equations (4:30 hours)</td><th colspan="2">Responsibility / Autonomy</th></tr>
<tr><td colspan="2">Autonomous use of thermal fluid-dynamics principles and balance equations (EQF=7)</td></tr>
<tr><th>Skills</th><th>Knowledge</th></tr>
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<td>• Basic Concepts about Fluids<br>• Fluid Models and Flow Regimes (single-phase)<br>• Balance Equations for Single-Phase Fluids<br>  ○ General Concepts<br>  ○ Useful Mathematical Relationships<br>  ○ Level of Detail in Balance Equations<br>  ○ Integral Lumped Parameter Equations<br>  ○ Partial Differential Balance Equations<br>  ○ Need for Closure Laws</td>
<td>• Being able to characterise the state of a fluid on the basis of commonly used thermodynamic diagrams<br>• Critical capability to select an appropriate flow model considering the intended application<br>• Ability to apply the Gibbs rule for determining the number of independent variables for a fluid in conditions of interest for nuclear reactors<br>• Ability to relate the basic laws of physics to the balance equations adopted in thermal fluid-dynamics<br>• Ability to convert surface integrals of advection and diffusion terms in balance equations to volume integrals<br>• Ability to write balance equations in Eulerian and Lagrangian form<br>• Capability to clearly explain the origin of the enthalpy function<br>• Ability to write and apply lumped parameter balance equations to simple systems (filling a volume of water, heat exchanger, forces on a pipe bend)<br>• Ability to retrieve the mass, momentum and energy equations from the general formulation of partial differential balance equations<br>• Ability to deal easily with differential operators (divergence and gradients of constant, vectors and tensors)</td>
<td>• Definitions and practical characterisation of fluids<br>• Distinction among the ranges of existence of vapour and gases, liquids and solids<br>• Reminder of p-T and p-v diagrams for a single component substance<br>• Distinction between the different fluid models adopted in thermal-hydraulics<br>• Understanding the characteristics and limitations of different fluid models (e.g., compressible vs., incompressible flows; viscous vs. inviscid fluids, etc.)<br>• Understanding the usefulness of the Boussinesq fluids approximation<br>• Extensive and intensive properties<br>• Concept of equilibrium<br>• Gibbs rule for variance determination<br>• General concept of balance and its applications in fluid-dynamics<br>• Eulerian and Lagrangian points of view for writing integral and differential equations<br>• Divergence theorem and of the Leibniz rule in deriving balance equations<br>• Understanding the relation between Eulerian and Lagrangian forms of balance equations<br>• Integral and differential balance equations: control volumes, control masses, points and particles</td>
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| | • Ability to retrieve from the general forms of balance equations the cases applicable to particular conditions; e.g.: continuity for an incompressible fluid; momentum for a fluid static condition; etc.<br>• Capability to derive the mechanical energy balance equation from momentum equation<br>• Capability to apply the Bernoulli equation for inviscid and incompressible fluids to typical practical situations: variable area ducts, Venturi nozzle, Pitot tube, Torricelli theorem case<br>• Capability to show the relation of the thermal energy equation in Lagrangian form to the 1st Principle of Thermo-dynamics<br>• General skills in applying balance equations in their different forms: no “fear” of mathematics<br>• Mastering the mathematical tools for balance equations and being able to apply them in particular cases of practical interest<br>• Capability to identify independent variables in balance equations, variables defined by the use of state relationships, variables needed constitutive laws | • Knowledge of lumped parameter equations for mass, energy and momentum in Eulerian and Lagrangian form and of their differences<br>• Understanding the role of enthalpy in the advection terms in energy equation<br>• Understanding the derivation and the general form of partial differential balance equations for a generic extensive property<br>• Bernoulli equation for inviscid fluid<br>• Understanding the role of Bernoulli in generating lift over an airfoil and in spinning bodies<br>• Knowing the difference between the Bernoulli equation and the generalised Bernoulli equation, also for compressible fluids<br>• Knowing and understanding the energy equation terms and its forms: total energy and thermal energy<br>• Understanding the need for state relationships and closure laws in balance equations for single phase fluids |
| ***Unit 2 – Laminar Flow, Navier-Stokes Equations and Boundary Layer Phenomena***<br>***(4:51 hours)*** | **Responsibility / Autonomy** | |
| | Autonomous use of thermal fluid-dynamics models for laminar flow conditions(EQF=7) | |
| | **Skills** | **Knowledge** |
| • Basic Concepts about Laminar Flow<br>• Newtonian and Non-Newtonian Fluids<br>• Short Overview on Non-Newtonian Fluids<br>• Laminar Flow of Newtonian Fluids<br>• Navier-Stokes Equations<br>• Dimensional Analysis of Navier-Stokes Equations | • Ability to use the convention for the definition of the shear stress on a surface orthogonal to an axis directed in the direction of another axis<br>• Ability to calculate a shear stress at the wall for different fluids given the velocity distribution<br>• Remembering the order of magnitude of viscosity for most important fluids (water, gases, etc.)<br>• Capability to write the components of the tensors of rotation and deformation rates | • Understanding at a basic level the difference between turbulent and laminar flow, Newtonian and non-Newtonian fluids<br>• Understanding the role of viscosity in the Newton’s law for shear stress and the role of shear stress components as a the negative of momentum fluxes<br>• Analogy between the kinematic viscosity and the thermal diffusivity |

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| • Typical Applications of Navier-Stokes Equations<br>• Few Concepts about Rotational and Irrotational Flows<br>• Boundary Layer Phenomena and Equations | • Being able to write the constitutive law for shear stress for Newtonian fluids in laminar flow<br>• Ability to write the Navier-Stokes equations and to explain the meaning of each term appearing in them<br>• Ability to discuss the appropriate boundary conditions to be applied to the Navier-Stokes equations and to the Euler equations<br>• Practical ability in making dimensionless the momentum balance equations to obtain dimensionless parameters<br>• Ability to solve classical problems related to laminar flow: smooth falling film and Poiseuille flow in a circular duct<br>• Ability to relate the Darcy-Weisbach and the Fanning friction factors on the basis of a force balance on the fluid in a circular pipe<br>• Ability to make use of the practical relationships for evaluating from drag and lift on typical bodies exposed to a free stream<br>• Ability to write the momentum equations for the 2D “boundary layer” approximation, explaining the approximations made to reach the related form | • Understanding the trends of viscosity with temperature for liquid and gases<br>• Knowing the behaviour of the main non-Newtonian fluid models<br>• Understanding the mathematical expressions for expansion and shrinking, rotation and deformation rates of a fluid element<br>• General constitutive law for the deviatoric stressing a fluid (general Newton’s law of viscosity)<br>• Knowledge and understanding of the development leading from momentum equation to the Navier-Stokes equations for laminar flow of a Newtonian fluid at constant density and viscosity<br>• Knowledge and understanding of the Euler equations<br>• Knowledge and understanding of the dimensionless parameters appearing in the dimensionless form of the Navier-Stokes equations and of the limit cases for large Re, Fr, etc..<br>• Clear understanding of the d’Alembert paradox<br>• Knowledge of the definition of “boundary layer”<br>• Clear understanding of the proposal of Prandtl about the partitioning of the flow into the two regions of boundary layer and the free stream<br>• Knowledge of the consequences of the Poiseuille-Hagen law<br>• Knowledge and understanding of the practical usefulness of the Darcy-Weisbach relationship and of the related friction factor<br>• Understanding the role of the reciprocal of the Re appearing in the Poiseuille law for laminar flow, in view of the Darcy-Weisbach relationship<br>• Understanding and remembering the difference between Darcy-Weisbach and the Fanning friction factors |

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| | | • Knowledge of the definition of the “hydraulic diameter” and understanding of its practical usefulness<br>• Knowledge of basic concepts about rotational and irrotational flows: vorticity, circulation, rigid body rotation, potential vortex, vorticity in the Couette flow, Kelvin theorem; understanding of their general meaning<br>• Knowledge of the structure of a fluid-dynamic boundary layer in laminar and turbulent conditions<br>• Understanding of the “favourable” and “adverse” pressure gradient conditions<br>• Knowledge and understanding (K&U) of wake phenomena with and without separation<br>• K&U of the pressure distribution over a bluff body assuming boundary layer separation: reminder of the d’Alembert paradox<br>• K&U of boundary layer transition phenomena at the entrance of a pipe in laminar and turbulent flows<br>• K&U of the approximations leading from the Navier-Stokes equations to their “boundary layer” approximation<br>• General understanding of the methodology adopted by Blasius for reaching the solution of the boundary layer equations in the case of zero pressure gradient, with main reference to: a) self-similarity of the solution; b) definition of the stream function; c) generality of the reached solution for a laminar boundary layer on a flat plate; d) consequences of the characteristics of the numerically determined profile on the evaluation of the shear stress at the wall |

| ***Unit 3 – Heat Transfer in Laminar Flow (3:17 hours)*** | **Responsibility / Autonomy** | |
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| | Autonomous use of thermal fluid-dynamics models for laminar flow conditions(EQF=7) | |
| | **Skills** | **Knowledge** |
| • Few Basic Remarks on Heat Transfer Mechanisms<br>• Thermal Energy Balance in Terms of Temperature<br>• Heat Transfer Problems in Laminar Flow<br>    ○ Thermal Boundary Layer over a Flat Plate<br>    ○ Heat transfer in a circular pipe with laminar flow | • Remembering the order of magnitude of thermal conductivity for several materials adopted in technical applications<br>• Remembering the order of magnitude of convective heat transfer coefficients in typical conditions<br>• Ability to make use of current textbooks and manuals on heat transfer to select the appropriate correlation for forced or free convection, external or internal flow<br>• Ability to write the different forms of the energy balance equations in terms of temperature<br>• Ability to relate the Blasius solution for the velocity distribution in a boundary layer to the corresponding solution for the thermal boundary layer in the case of Pr=1 and in the case of $Pr \neq 1$<br>• Remembering the order of magnitude of the heat transfer coefficient in a laminar flow in a circular pipe, also considering the different boundary conditions<br>• Ability to select from heat transfer textbooks the appropriate thermal entry length correlations | • Knowledge of the basic laws of heat conduction<br>• Understanding the problem of the transient behaviour of a flat plate with convective boundary conditions on the two surfaces<br>• Dimensional analysis of the above problem<br>• Knowledge and understanding of the main dimensionless parameters appearing in the dimensionless form of the above problem<br>• Knowledge of the basic laws of heat convection<br>• Meanings of the Nusselt number<br>• Knowledge and understanding of the meaning of the main dimensionless parameters appearing in correlations for heat transfer in forced and free convection: Re, Gr, Pr, $Gr/Re^2$<br>• General K&U of the main phenomena and relationship to be considered in heat radiation problems: coefficients of emissivity, absorption and transmission; Boltzmann's constant and the basic law of radiation; grey bodies; view factors; radiosity<br>• Understanding the root of the different forms of thermal energy balance equation written in terms of temperature<br>• Understanding the role of viscous dissipation of heat (e.g., in the warming up of a reactor plant by pumps)<br>• K&U of the dimensionless numbers appearing in the dimensionless form of the energy balance equation (Pe, Br)<br>• K&U of the limit forms of the energy balance equation for a still fluid or a solid (the "heat equation") |

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<tr><td></td><td></td><td><ul><li><u>Clear understanding</u> of the basis of the analogy between heat and momentum transfer considering the related energy and momentum equations in boundary layer form</li><li>Understanding the role of the Stanton number</li><li>Understanding the developments leading to the evaluation of the convective heat transfer coefficient in laminar flow in a circular pipe</li><li>K&U of the effects of flow and thermal development at the entrance of a pipe on heat transfer: Graetz number and thermal and combined entry length problems</li></ul></td></tr>
<tr><td rowspan="3">Unit 4 – Momentum and Heat Transfer in Turbulent Flow (4:47 hours)</td><td colspan="2">Responsibility / Autonomy</td></tr>
<tr><td colspan="2">Autonomous use of thermal fluid-dynamics models for turbulent flow conditions (EQF=7)</td></tr>
<tr><td>Skills</td><td>Knowledge</td></tr>
<tr><td><ul><li>General Remarks on Turbulent Flow</li><li>Statistical Treatment of Turbulent Flow</li><li>Momentum Transfer in Turbulent Flow<ul><li>Eddy Viscosity</li><li>Velocity distribution in turbulent flow</li><li>Distributed Pressure Drops and Friction Factors in Turbulent Flow</li><li>Singular Pressure Drops</li><li>Few remarks on Pump Characteristics</li></ul></li><li>Heat Transfer in Turbulent Flow<ul><li>Eddy Diffusivity</li><li>Reynolds Analogy for Flow on a Flat Plate</li><li>Heat Transfer in Ducts with Forced Convection</li></ul></li></ul></td><td><ul><li>With the aid of the Van Dyke photographic textbook, clarify your understanding of the transition to turbulence in different conditions</li><li>Capability to distinguish between turbulence intensity and turbulence kinetic energy and to write the related definitions</li><li>Capability to write the general balance equation for a given extensive property in time-averaged form, clearly identifying the meaning of each term</li><li>Capability to explain the classical trends of turbulence intensity and turbulent and viscous shear stresses with the distance from a wall</li><li>Remembering the classical definitions of w+ and y+ quite often adopted in turbulence</li><li>Capability to draw a qualitative sketch of the radial distribution of velocity in a pipe in laminar and turbulent conditions</li><li>Capability to draw the Moody diagram explaining all its relevant features</li><li>Remembering the order of magnitude of friction factor in typical turbulent flow conditions ($2\text{-}3\times10^{-2}$)</li></ul></td><td><ul><li>Understanding the origin of instabilities leading to turbulence in different fluid systems (flat plate, pipes, jets, wakes from bluff bodies)</li><li>Clear understanding of the basics and the purposes of the statistical treatment of turbulence flow by Reynolds</li><li>K&U of the classical process of writing balance equations in terms of time averaged variables and of the change of perspective in considering <u>the residual terms coming from advection as diffusion due to turbulence</u></li><li>K&U of the concepts of eddy viscosity and eddy diffusivity as used in the Boussinesq assumption and in the treatment of turbulent heat flux</li><li>Knowledge of classical algebraic models for taking into account eddy viscosity</li><li>K&U of the arguments at the basis of the derivation of the classical universal profile of velocity in a turbulent boundary layer</li><li>Clear K&U of the following aspects:<ul><li>trend of frictional pressure drop as a function of velocity in a smooth pipe for turbulent and laminar flow</li></ul></li></ul></td></tr>
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| ○ Remarks on Heat Transfer in Free Convection | • Remembering the order of magnitude of pipe roughness [m] for different pipe materials<br>• Capability to identify the most important singular pressure drops occurring in a series of pipes on the basis of the gallery presented in the lecture notes and available in the suggested textbooks<br>• Capability to select the appropriate singular pressure drop coefficients for the different irregularities present in a pipe on the basis of suggested textbooks<br>• Ability to discriminate among the different types of valves in terms of their pressure drops<br>• Ability to calculate the hydraulic diameter for different pipe cross sections and to make use of it in correlations<br>• Ability to evaluate the required pump power on the basis of the delivered head and of flow rate; ability to determine the required motor power<br>• Remembering the classical heat transfer correlations for forced flow in single-phase conditions<br>• Ability to recognise and adopt the classical corrections for heat transfer accounting for entrance effects<br>• Ability to clearly explain the use of the "Boussinesq fluid" assumption in free convection problems (why constant density almost everywhere, except for the evaluation of buoyancy effects?)<br>• Being able to select the most appropriate free convection heat transfer correlation for a given situation using handbooks. | ○ detailed features of the Moody diagram for friction factor<br>○ approximate laws for friction factors in turbulent flow in smooth pipes (Blasius and McAdams)<br>• Knowledge of the existence of several numerical approximation of the Moody diagram (Colebrook, Swamee & Jain, Churchill)<br>• K&U of the reasons leading to singular pressure drops on the basis of the phenomena leading to kinetic energy dissipation (separation of boundary layer, vena contracta, recirculations in bends, etc.)<br>• K&U of the main working characteristics of a pump: determination of the working point, meaning of NPSH (requested and available, control of flow by "downstream" valve throttling)<br>• K&U of the relationship leading to evaluate turbulent heat flux on the basis of thermal eddy diffusivity<br>• K&U of the Reynolds and Colburn analogies for heat and momentum transfer and of its consequences in deriving forced flow heat transfer correlations<br>• K&U of the entrance effects in turbulent flow and of the different approaches<br>• K&U of the general principles at the basis of the treatment of free convection flows |
| ***Unit 5a – Natural Circulation in Single-Phase Flow (1:33 hours)*** | **Responsibility / Autonomy** | |
| | Autonomous use of thermal fluid-dynamics models for predicting natural circulation (EQF=7) | |
| | **Skills** | **Knowledge** |
| • Balance Equations for One-Dimensional Single-Phase Flow<br>• Single-Phase Natural Circulation<br>• Application | • Ability to apply momentum and energy balance equations for a simple natural circulation loop to calculate the steady state flow rate | • Knowledge of the importance of natural circulation in industry, with reference to nuclear reactor applications<br>• Understanding the process of obtaining balance equation for natural circulation of a Boussinesq fluid |

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| • Single-Phase instabilities: strange but true! | • Ability to calculate the steady state natural circulation flow rate in a simple loop given the heating power, the characteristics of the fluid and the geometry of the loop | • Understanding the role of buoyancy and friction in determining the steady state flow rate in a natural circulation loop<br>• General knowledge of the problems involved in the occurrence of unstable behaviour in single phase natural circulation loop |
| ***Unit 5b – Notes on Compressible Single-Phase Flow (1:18 hours)*** | **Responsibility / Autonomy** | |
| | Autonomous use of models for compressible flows (EQF=7) | |
| | **Skills** | **Knowledge** |
| • General Considerations<br>• Sound Speed<br>• The Hugoniot relationship<br>• Critical Flow in a convergent duct<br>• The de Laval nozzle | • Ability to calculate the sound speed for an ideal gas<br>• Ability to apply the relationship for calculating the critical flow of an ideal gas given its upstream conditions<br>• Capability to explain the main features of the pressure and velocity distributions in a de Laval nozzle. | • Definition of compressibility and its relation to the sound speed<br>• Definition of sound speed and understanding of its derivation<br>• Understanding the effect that a finite sound speed introduce in the propagation of information in a flowing fluid: 1D and multi-d cases<br>• Knowledge of the Hugoniot relationship and understanding of its consequence for converging-diverging ducts with compressible flows<br>• Understanding the reasons for the establishment of critical flow in a converging pipe |
| ***Unit 5c – More on Turbulence ( (1:59 hours)*** | **Responsibility / Autonomy** | |
| | Autonomous use of turbulence models (EQF=7) | |
| | **Skills** | **Knowledge** |
| • Length Scales in Turbulence<br>• Direct Numerical Simulation<br>• Large Eddy Simulation<br>• Reynolds Averaged Navier-Stokes Equations<br>• Algebraic Models<br>• One-Equation Models<br>• Two-Equation Models | • Ability to schematically draw the spectrum of turbulent energy distribution, explaining its relevant features<br>• Ability to clearly explain the differences between the DNS, LES and RANS techniques making reference to the energy cascade and to the spectrum of turbulent kinetic energy<br>• Ability to recognise in the equations for the turbulence stresses and turbulence kinetic energy the transient, advective, diffusive and source-sink terms | • Understanding the concept of energy cascade and the role of dissipation of turbulent kinetic energy<br>• Understanding the meaning of the Kolmogorov scales of turbulence<br>• Understanding the reasons why the turbulence phenomenon can be studied in the assumption of the fluid as a continuum<br>• Understanding of the main features of DNS techniques in relation to the energy cascade |

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| • Considerations on meshing at the wall: wall functions and low y+ refinement | • Ability to write in a basic form the transport equation for turbulence kinetic energy<br>• Capability to write and describe the main features of the transport equations of two-equation turbulence models<br>• Discriminating the need for using wall function or low-Reynolds approaches at the walls | • Understanding the main features of LES techniques and their differences with respect to DNS, on one side, and RANS, on the other<br>• Understanding the role of spatial “filtering” in LES and of the need for subgrid scale models<br>• Understanding the role of time averaging in RANS models and the different levels of closure (zero, one and two equations)<br>• K&U of the mixing length model as a representative of the class of algebraic models<br>• Understanding the need for transport equations to track the effects of turbulence in space and time<br>• Understanding the process necessary to derive transport equations for the components of the specific Reynolds stress tensor and for turbulence kinetic energy<br>• Understanding the need for closures in one-equation models and the issue of their incompleteness<br>• Understanding the link between the calculation of k, $\varepsilon$ and turbulent viscosity<br>• Understanding the need for two equation models for achieving some degree of completeness in turbulence modelling<br>• K&U of the form of k-$\varepsilon$ and k-$\omega$ transport equations<br>• Understanding the difference between the use of “wall functions” and the adoption of low-Reynolds number models |
| ***Unit 6 – Two-Phase Flow: General Definitions, Flow Regime Maps and Balance Equations (8:09 hours)*** | **Responsibility / Autonomy** | |
| | Autonomous use of two-phase flow balance equations (EQF=7) | |
| | **Skills** | **Knowledge** |
| • General Definitions<br>• Flow Regimes<br>  ○ Main Observed Phenomena<br>  ○ Flow Regime Maps | • Ability to relate basic characteristic two-phase variables with each other in combinations useful for writing correlations | • Knowledge of the main variable useful for characterising two phase flow<br>• Knowledge of the relation between void fraction, dynamic quality and slip ratio |

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| ◦ Flow Regime Transition Criteria<br>• Balance Equations for Two-Phase Flow<br>◦ General Remarks<br>◦ One-Dimensional Homogeneous Equilibrium Model<br>◦ One-Dimensional Two-Fluid Model<br>◦ Remarks on Balance Equations for Two-Phase Flow<br>◦ Semi-empirical Approaches for Mixture Models<br>◦ Mathematical Character of Balance Equations for Two-Phase Flow | • Capability to use flow regime maps and phase transition criteria to approximately establish the existence of a flow regime<br>• Capability to write and explain the main differential ans source terms in two-phase flow balance equations with different levels of approximation<br>• Capability to apply void-quality relationship to evaluate void fraction by the drift-flux model | • Flow regimes in vertical adiabatic and heated ducts<br>• Heat transfer and flow regimes in a vertical boiling pipe<br>• Flow regimes in horizontal flow<br>• Flow regime maps and their use: flow regime transition criteria<br>• Flow regime maps as implemented in system codes<br>• Form of the one-dimensional Homogeneous Equilibrium two-phase balance equations and their derivation<br>• One dimensional two-fluid model equations and their derivation form first conservation principles<br>• Usual form of the balance equations for two-phase flow with thermal and mechanical non-equilibrium: main assumptions underlying their derivation<br>• Drift flux model in the Zuber-Findlay and Wallis forms<br>• Mathematical character of two-phase flow equations and ill-posedness of some two-fluid models |
| ***Unit 7 – Pressure Drops and Heat Transfer in Two-Phase Flow (6:10 hours)*** | **Responsibility / Autonomy** | |
| | Autonomous use of models for pressure drop and heat transfer in two-phase flow (EQF=7) | |
| | **Skills** | **Knowledge** |
| • Pressure Drops in Two-Phase Flow<br>◦ General Definitions<br>◦ The Homogeneous Equilibrium model<br>◦ The Lockhart and Martinelli Model<br>◦ The Martinelli-Nelson Model<br>◦ Other Models<br>◦ Codes and Two-Phase Pressure Drops<br>• Boiling Heat Transfer<br>◦ Conditions for the Occurrence of Boiling | • Capability to apply the two-phase flow multipliers to evaluate pressure drops: use of classical diagrams for relevant parameters<br>• Capability to identify in the relevant literature and apply the appropriate heat transfer correlations according to an identified boiling heat transfer regime<br>• Mastery of concepts and definitions of relevant parameters entering correlations for heat transfer in boiling conditions<br>• Explaining the mechanisms of decrease of condensation heat transfer efficiency in the presence of noncondensable gases | • Two-phase flow multipliers for two-phase pressure drops in the different existing forms<br>• Understanding how the two-phase flow multiplier approach (mixture model) may be applied in two-fluids models (separated flow models)<br>• Mechanical equilibrium between pressure and surface tension in a bubble and its consequence for liquid superheating at boiling inception<br>• Phenomena in pool boiling and the Nukiyama curve<br>• Correlation for pool boiling and its incipience in the various regions of the Nukiyama curve<br>• Phenomenological description of the boiling crisis (CHF, DNB, dry-out) in pool and flow boiling<br>• Definitions of DNBR, MCHFR and MCPR |

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| ○ Phenomenological Description of Pool Boiling<br>○ Quantitative Evaluation of Pool Boiling Phenomena<br>○ Phenomenological Description of Flow Boiling<br>○ Quantitative Evaluation of Flow Boiling Phenomena<br>• Condensation<br>○ General Remarks<br>○ Filmwise Condensation<br>○ Effect of Noncondensable Gases<br>○ The analogy between Heat and Mass Transfer<br>○ Superposition of latent and convective heat transfer during condensation<br>○ Two-Phase Heat Transfer in Codes | • Explaining the applicability of the analogy between heat and mass transfer in condensation (and evaporation) conditions | • Classical graphical representation of CHF and heat transfer phenomena in the plots of the collier "Boling and Condensation" textbook<br>• Correlations for heat transfer in flow boiling<br>• Approaches and correlations for DNB and dry-out in flow boiling: Tong F-factor critical quality-critical boiling length approaches<br>• Filmwise condensation phenomena in the case of pure vapours: Nusselt theory<br>• Effect of noncondensable gases on condensation, analogy between heat and mass transfer, Colburn-Hougen approach for superposing latent and sensible heat transfer during condensation<br>• General knowledge of the treatment of heat transfer in system codes for thermal-hydraulic safety analyses |
| ***Unit 8 – Some Specific Phenomena in Two-Phase Flow: Critical Flow, Flooding and Boiling Channel Instabilities***<br>***(2:37 hours)*** | **Responsibility / Autonomy**<br>Autonomous use of models for critical flow, flooding and boiling channel instabilities (EQF=7) | |
| | **Skills** | **Knowledge** |
| • Critical Flow<br>○ General Description of the Phenomenon<br>○ Importance of the Phenomenon for Nuclear Technology<br>○ Mathematical Explanation of the Phenomenon | • Use of the characteristic lines to explain the existence of chocked flow<br>• Describing the use of the "characteristic equation" to determine chocked flow conditions for a give two-phase flow model<br>• Capability to discriminate between different chocked flow models for a given nuclear reactor application<br>• Capability to explain the reasons for the occurrence of flooding and CCFL | • Phenomenological and mathematical understanding of chocked flow<br>• Two-phase, thermal equilibrium critical flow models: HEM, Fauske and Moody models<br>• Non-equilibrium modelling of critical flow in two-phase conditions<br>• Phenomenological description of flooding and CCFL phenomena in bare pipes and in nuclear fuel bundles<br>• Wallis type interpretation of flooding and CCFL |

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| <ul><li>Reminder of Critical Flow for a Perfect Gas</li><li>Two-Phase Critical Flow Models</li></ul><ul><li>Flooding<ul><li>Phenomenological Description</li><li>Quantitative Prediction</li></ul></li><li>Boiling Channel Instabilities<ul><li>Classification of Instabilities</li><li>Static Instabilities</li><li>Dynamic Instabilities</li><li>Tools for Predicting Boiling Instabilities</li></ul></li></ul> | <ul><li>Application of existing correlations for predicting flooding</li><li>Capability to explain the effect of different parameters in static and dynamic two-phase flow instabilities</li><li>Capability to show on a NPCH-NSUB plane the regions for different kinds of instabilities</li></ul> | <ul><li>Wallis and Kutateladze dimensionless parameters for correlating flooding phenomena</li><li>Classification of two-phase flow instabilities into static and dynamic: different types of instabilities</li><li>Ledinegg instability and approximate justification of its occurrence</li><li>Density wave oscillation instabilities and their physical roots</li><li>Dimensionless parameters for the characterisation of two-phase flow instabilities</li><li>Parametric effects on the occurrence of density wave instabilities</li><li>Time-domain and frequency domain approaches for predicting instabilities</li><li>Instabilities in BWRs and “exclusion region” in the power-flow map of a boiling water reactor</li></ul> |
| ***Unit E1 – Basic Exercises on Heat Conduction (5:32 hours)*** | **Responsibility / Autonomy** | |
| | Autonomous use of quantitative evaluation techniques for predicting heat conduction (EQF=7) | |
| | **Skills** | **Knowledge** |
| <ul><li>Summary of analytical techniques to solve heat conduction problems</li><li>Transient heat conduction in a flat plate by numerical models</li><li>Steady-state heat conduction in a 2D domain by numerical models</li><li>Steady-state and transient temperature distribution in a nuclear fuel rod by manual calculations and numerical models</li></ul> | <ul><li>Capability to apply well-known results from the integration of the heat conduction equation</li><li>Use of the MATLAB routine for transient heat conduction in a flat plate and critical discussion of the obtained results</li><li>Use of the MATLAB routine for steady state heat conduction in a 2D domain and critical discussion of the obtained results</li><li>Manual calculations of the steady state temperature distribution in a nuclear fuel rod of given geometry and properties and use of the MATLAB routine in transient conditions with critical analysis of the results; simulation and explanation of the effects of temperature redistribution in the presence of SCRAM and critical heat flux conditions</li></ul> | <ul><li>Analytical techniques for solving heat condutions problems</li><li>Understanding a MATLAB routine for numerically calculating the transient temperature distribution in a flat plate with Dirichlet ($1^{st}$ kind) boundary conditions</li><li>Understanding a MATLAB routine for numerically calculating the steady state distribution of temperature in a rectangular 2D domain with assigned volumetric power, geometry and thermal properties</li><li>Understanding a MATLAB routine for numerically calculating the transient behaviour of a nuclear fuel rod and comparing the numerical equations with the classical manual solution for temperature drops in a nuclear fuel rod</li></ul> |

| *Unit E2 – Examples of Application of Lumped Parameter Balance Equations (5:20 hours)* | **Responsibility / Autonomy** | |
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| | Autonomous use of quantitative evaluation techniques for predicting two-phase flow in large capacitances (EQF=7) | |
| | **Skills** | **Knowledge** |
| • Lumped parameter two-phase flow models | • Capability to apply the equations to pressurization and depressurization of the capacity because of inflow and outflow: critical discussion of the results: manual calculations<br>• Compare the capabilities of the equilibrium and non-equilibrium models in the application to nuclear reactor components (e.g., the pressurizer)<br>• Describe the limitations of each model to treat non-equilibrium phenomena between the phases and in each phase<br>• Ability to critically discuss simulated thermal hydraulic phenomena for the non-equilibrium two-phase flow capacity knowing the model and its limitations<br>• Ability to calculate an approximation of the first pressure peak in a dry containment given the initial conditions and the mass and energy release | • Lumped parameter balance equations for a two-phase capacitance with thermal equilibrium between liquid and vapour<br>• Understanding a FORTRAN program implementing the above balance equations<br>• Lumped parameter balance equations for a two-phase capacitance with thermal non-equilibrium between liquid and vapour<br>• Understand the plotted results of obtained by a non-equilibrium code model for different inflow and outflow cases<br>• Approximations to perform hand calculations of the first pressure peak after a LOCA in a dry containment, knowing the initial mass and energy content in the primary system and other relevant information |
| *Unit E3 – Basic Balances for LWRs (2:07 hours)* | **Responsibility / Autonomy** | |
| | Autonomous use of simple quantitative evaluation techniques for LWR analysis (EQF=7) | |
| | **Skills** | **Knowledge** |
| • Basic mass and energy balances in PWRs<br>• Basic mass and energy balances in BWRs and Steam Generators | • Capability to perform simple single-phase fluid hand calculations along a the subchannel of a PWR core with usual simplifying assumptions. Calculation of core flow rate given the thermal power and the typical temperature difference across the reactor core<br>• Capability to apply the simple mass and energy balances in a BWR vessel to calculate the main parameters | • Basic equations to evaluate the coolant temperature distribution along a PWR subchannel estimating the temperatures in the fuel centreline and at the clad surface<br>• Basic energy balances in a BWR core (or in a Steam Generator) for analysing core, recirculation and steam line flows |
| *Unit E4 – Basic Applications of CFD Codes* | **Responsibility / Autonomy** | |
| | Critical interpretation of the results of a CFD code (EQF=7) | |

| ***(4:18 hours)*** | **Skills** | **Knowledge** |
|---|---|---|
| • Flow in circular pipes<br>• Heat transfer to water at supercritical pressure<br>• Condensation in the presence of noncondensable gases<br>• Flow in a reactor vessel | • Discussing the different options available in CFD codes for simulating problems of interest for heat and mass transfer | • Application of the STAR-CCM+ code to turbulent flow in a pipe with an upward bend in 3D<br>• Application of the STAR-CCM+ code to turbulent flow in a in a heated pipe with incompressible fluid in 2D<br>• Application of the STAR-CCM+ code to turbulent flow in a in a heated pipe with supercritical pressure water in 2D<br>• Modelling condensation rates over a flat plate (CONAN Facility installed at UniPi)<br>• Description of discretisations for reactor downcomer and plenum |
| ***Unit E5 – Basic Applications of the RELAP5 Code (1:47 hours)*** | **Responsibility / Autonomy**<br>Critical interpretation of the results of a system code (EQF=7) | |
| | **Skills** | **Knowledge** |
| • Essential summary on balance equation discretisation by the RELAP5 code<br>• Boiling channel stability<br>• Natural and gas-injection enhanced circulation in a loop | • Discussing the way of modelling flow systems by system code components | • Basics about numerical discretisation by a staggered mesh method: nodes and junctions<br>• Instability phenomena in a BWR single-boiling channel with imposed pressure drop<br>• Natural and gas-injection enhanced circulation phenomena in an experimental loop (ANGIE Facility at UniPi and CIRCE facility at ENEA Brasimone) |
| **Assessment criteria** = to demonstrate mastery of basic thermal-hydraulic phenomena and simulation techniques for nuclear reactor applications | | |
| **Recommended assessment methods:** Written test and oral face to face interview | | |

A Video having a duration of 39 m is added to provide guidelines

**Course applicable (in part or fully) for the following job profiles:**

<u>Nuclear Experts (16% in EHRO-N analysis) and "Nuclearised" Experts:</u>

1.0.02 Safety Assessment Specialist

1.0.10. Safety Design Engineer

1.2.01. Design Manager

1.2.12. HVAC Design Engineer

2.0.01. Plant Manager

2.1.06. Engineering Manager

2.1.07. Operation Manager

2.1.02. Licensing Officer

2.1.04. Training Officer

2.5.01. Chemistry Manager

2.6.01. Safety and Security Manager

The course is also applicable to the basic education of **future researchers, University teachers and Industry trainers** in nuclear reactor thermal-hydraulics