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TOPIC ②

MECHANICS

2.1 Thermal-hydraulics

2.1.1. Thermal-hydraulics for reactor applications and current state of the art codes

Part 1 From balance equations to simulation of fast transients and critical single- and two-phase flows

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1.- **Introduction**

The analysis of transient and accidental processes in Nuclear Power plants requires the use of accurate computer codes [1]. One distinguishes between “system codes”, “containment codes”, severe accident codes”, “CFD codes”, “coupled codes” and many other codes dedicated to the simulation of particular phenomena, such as the water hammer [2]. The best estimate character of system codes involves an evaluation of the uncertainties of the predicted plant transients. This is achieved for example in the BEMUSE project of the OECD [3].

The accurate modelling of the complex transport phenomena that occur in nuclear installations requires a reliable set of single-, two- and sometimes multi-phase flow equations. These equations consist in balances of mass, momentum (linear and angular), energy and entropy on the one side, and closure laws on the other. For a fine description of the flows and heat transfer processes, the independent variables are the spatial coordinates and time. However, usually, a complete local and instantaneous description of the flow is not needed or possible. The user is more interested in properties averaged over space and time, based on which the control of the processes can be designed and validated. Obvious examples of the need for averaging are given by the turbulent fluctuations or the bubble diameter distributions, or by such an important control parameter as the flow rate, which, by definition is an instantaneous area averaged quantity.

Independent on the wishes of the user to work with “simple” models, several phenomena are local by nature. This is the case for example of the onset of nucleation which corresponds to a local minimum condition of an activation energy; it is also the case of the critical heat flux (CHF) which corresponds to the presence of vapour during a minimum time span at a hot spot, etc.

Other phenomena can be accurately described by averaged equations like the choked flow at a pipe breach in the Loss of Coolant Accidents (LOCA), or wave propagations in pipes.

In this lecture, the space averaging process of the equations is described as well as the need for closure laws [4], [5], [6]. Although the same process is of use for single- or two-phase flows, the interface jump conditions make the derivations more complicated in the latter case.
Having established the instantaneous area averaged equations for a single-phase flow, we will show how they can be applied for the prediction of water hammers

2.- Reminder: Single-phase flow equations: from balance equations in a material volume to local equations

From the generalised balance equation, thanks to the Leibniz rule and the divergence theorem, one can deduce the local equations of mass, momentum, total (stagnation) energy and entropy. The kinetic energy equation is deduced from the momentum equation by its scalar product with the velocity. Then, subtracting the kinetic equation from the total energy equation, the internal energy or its equivalent the enthalpy equation is obtained. Finally, the entropy source term, which is always positive according to the second law of thermodynamics is deduced from the Gibbs equation and the local balance equations. In order to close the set of equations, it appears that an equation of state of the fluid, a mechanical and a thermal constitutive laws of the fluid, the gravity and the heat volumetric source are needed. The particular case of the Navier-Stokes equation is presented, and the Reynolds averaged equation for turbulent flows is mentioned.

3.- Integration of the single-phase equations over the cross-section of a channel; usual approximations of the 1D models

The integration of the local equations over the cross-section involves the use of the limit forms of the Leibniz rule and of the divergence theorem for an area. The local equations of mass, momentum and internal energy are integrated, and a set of eleven simplifying assumptions are successively introduced. Focus is made on the terms involving the pressure, and the friction losses: one of the usual assumptions consists indeed in considering that the average pressure in the cross section is equal to the average pressure along the intersection of this cross-section and the wall. It is also interesting to observe the difference in significance between the friction term in the averaged momentum equation, and the average friction dissipation in the cross-section. It is reminded that neglecting the compressibility of the fluid leads to an infinite speed of sound, and thus an infinite critical flow rate, and that neglecting the mechanical energy term in the internal energy equation leads to a non-realistic speed of sound. Finally, the set of usual 1D equations is presented and the evolution of the entropy at the average velocity (flow rate) is presented and can be easily interpreted. In steady state, it is shown that the 1D model enables to predict the correct the critical mass velocity.

4.-A closure law for the wall friction of fast transient single-phase flows

The water hammer is an example of relevant fast transient adiabatic flow for nuclear power plants. First, the frictionless low instantaneously interrupted by the closure of a valve is taken as an example to show the inadequacy of the predictions made by several system codes. Then, the prediction of the wall shear-stress evolution during and after the passage of a pressure wave through the channel is analysed with the FLUENT® CFD code. It appears that in a first phase the shear-stress is suddenly modified and can be estimated from the Joukowsky relation, while, after the passage of the wave, a relaxation takes place that can be predicted by means of Extended Irreversible Thermodynamics [7], [8], [9].

5.-From two-phase flow integral balance equations to local equations

Starting from the generalised integral balance equation applied to a two-phase fixed open volume of fluid, the local generalised phase equation and the generalised jump condition at the interface are established by means of the Leibniz rule and the divergence theorem.

6.-From local equations to equations averaged over the cross-section of the channel; usual approximations of the 1D models

The integration of the phase generalised local equation is performed over a cross-section of a channel by means of the limit forms of the Leibniz rule and of the divergence theorem. Then the averaged equations of mass, momentum and total energy are written for each phase. The physical meaning of each term is presented, in particular for the terms expressing the exchanges between the phases. A set of eight classical simplifying assumptions is shown in order to derive the classical two-fluid model (1D equations). In particular, the assumption of equality of the pressures in the two phases is discussed, and it is shown by means of an example that this assumption is not valid for horizontal stratified flow. Finally, the two-phase or mixture equations are obtained by summing up the corresponding phase equations.

7.-Choked or critical flow

Choked or critical flow is selected for this lecture because of its relevance for LOCA analyses and also because the speed of sound is linked to the choice of the flow model. Indeed, once the closure laws have been determined, the critical flow is given by the vanishing condition of the determinant of the system matrix. Thus, it should not be artificially introduced by an additional model.
First the physics of the choked flow phenomenon is reminded and its importance in nuclear as well as chemical safety is underlined. The single-phase modelling already mentioned in

section 3 is detailed. For two-phase flows, two basic and opposite models are described: on the one side the Homogeneous Equilibrium Model (H.E.M.) ,which assumes that the interface exchanges are so strong that mechanical and thermodynamic equilibriums are achieved along the flow path including at the critical section; on the other side, the Frozen Flow Model (F.F.M.), which is a two-fluid model where the interfacial exchanges are inexistent (frozen) at the critical section. While H.E.M. seems to systematically underpredict the critical mass velocity, F.F.M. overpredicts it. The solution consists in better modelling the mechanical as well as the thermodynamic non-equilibriums thanks to interfacial transfer laws involving derivatives of the variables. It is briefly shown that in absence of mass transfer (two-component flows), the mechanical non-equilibrium can be modelled by due consideration for the added mass terms of the momentum equations, possibly leading to a relaxation law for the slip between the phases [10], [2] . For flashing flows [11] [12], two models are compared, both using a relaxation law for the thermal non-equilibrium: the Delayed Equilibrium Model (D.E.M.) [13] and the Homogeneous Relaxation Model (H.R.M.). D.E.M. has been validated by means of more than 500 sets of data, including different fluids, geometries, subcoolings, and is presently under implementation in the CATHARE code. In the past, it has been applied to the modelling of the flows through steam generator cracks [14]. Presently some efforts are devoted to the modelling of cavitation with the NEPTUNE CFD code [15].

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