EAC-Analysis of Hypothetical LOF and TOP Accidents with Emphasis on the ICE-Type Finite Element Hydrodynamic Module EACMAND

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Summary

EAC is a multichannel modular computer code oriented towards the simulation of hypothetical whole core accidents in LMFBRs (e.g. loss of flow or transient overpower events). The code presents itself as an informative support receiving various stand-alone modules which are put together to become interactive in the framework of a whole core model. Neutronics, fuel behaviour and sodium thermohydraulics are the main phenomena which interact during the initiating phase of almost all hypothetical whole core accidents. The scope of this paper is to illustrate some of the physics which lies behind the assembling process of such codes. As a matter of fact modifications may be necessary in some of those modules in order to account for new boundary conditions (e.g. on the inlet pressure instead of the inlet velocity) and new heat source specifications (e.g. clad-coolant heat transfer instead of given power history). Attention is focused also to the computational aspects which should lead to the usual compromise between improved versatility and accuracy together with reduced CPU-time consumption. Along these lines it is shown that EAC makes realistic predictions of the neutronic behaviour of the whole core: the resulting temperature distributions in fuel, structures and coolant are then the leading parameters for further thermo-mechanical study towards the accident termination. Emphasis is given in particular to the homogeneous boiling model EACMAND which is discretized in a ICE-type finite element format. The typical tridiagonal matrix formulation of the ICE-technique has long been recognized useful in solving boundary-value problems in thermohydraulics and its semi-implicit treatment of the main variables allows for relatively large time-steps. On the other hand, to treat complex configurations such as the variable flow area of a coolant channel, a finite element approach is usually recommended. As a matter of fact, one-dimensional finite elements are considered in space (z-dimension) with linear velocity fields and uniform pressure, enthalpy and vapour quality. This unusual marriage (ICE technique plus finite element method) in two-phase flow analysis is proven here to be very competitive in the framework of a comparative exercise involving various thermohydraulic computer codes.
1. Introduction

To achieve a better understanding of the dominant physical phenomena in the safety analysis of LMFBFRs, especially in transient conditions, a deterministic approach is by far more suitable than any probabilistic method of the fault tree/event tree type. In conceiving hypothetical accidents for LMFBFRs, one considers usually two broad categories: local fault events and whole core accidents (WCA). A typical local fault event, for example, consists of a partial blockage in a single fuel or blanket assembly, which generates usually only minor power changes. In whole core accidents, on the other hand, one considers chains of events which may lead to hypothetical core disruptive accidents (HCDA) where the plant protection system is assumed inoperative after an undercooling or overpower initiating event: this category of events generally involves large power changes (prompt critical excursions).

For these types of HCDA events the whole plant simulation is not necessary since disassembly would occur faster than the time required for sodium to complete one pass through the heat transport circuit. The scope of this paper is to focus on dynamic simulation of the core only, making use in particular of the European Accident Code (EAC) which is a modular informatic frame developed at the Joint Research Centre of Ispra with the aim of receiving various stand-alone programs. The emphasis is given in particular to the physical modelling and the numerical computation of the thermohydraulics which is one of the most sensitive phenomena of the whole core behaviour in accidental situations.

At the moment EAC deals only with the initiating phase of hypothetical accidents such as loss-of-flow (LOF) and transient overpower (TOP). The code EAC gives a detailed description of the primary power excursion induced by sodium voiding, followed by a possible shut-down phase due to fuel motion under dispersive forces after fuel pin failure. New modules are foreseen, however, to deal with the early transition phase. In this way EAC appears to be an appropriate instrument to predict possible accident scenarios in a much more realistic way than what results from the often inconsistent bounding studies based on questionable source terms.

2. Thermal Feedbacks in WCA analysis

Thermal feedbacks, actually, play a key role in the dynamic behaviour of LMFBFRs, as it is illustrated on the closed loop model of the neutronic behaviour in Fig. 1. A change in the operational characteristics of a fast breeder, especially in the command parameters (i.e., thermal power, coolant flow and inlet temperature in the core), induces a variation of the core reactivity which acts as a thermal feedback effect. This change in reactivity, and hence in thermal power, is relatively prompt-acting and may lead in some severe accident situations to a dramatic power excursion. As a consequence it is of crucial importance to compute correctly the closed loop system of Fig. 1 in order to get a correct prediction of this first power excursion. Only then, and provided no shut-down mechanism terminates the accident, it is really worth to use sophisticated codes of neutronics, hydrodynamics and structural analysis to compute the further events in the accident chain.

In a first step the development of EAC consisted in gathering together from national laboratories well-tested stand-alone programs dealing with one of the following key phenomena:

i) neutron kinetics ($r \approx 10^{-6}$ sec)

ii) heat transfer and fission gas behaviour in the fuel pin ($r \approx 2$ sec)

iii) single-phase ($r \approx 1$ sec) and two-phase ($r \approx 0.001$ sec) hydrodynamics of sodium.

Because of the modular structure of EAC one is forced in fact to couple those phenomena in a weak manner, that is: neutronics, fuel behaviour and hydrodynamics must be calculated sequentially, at each time step, whereas a simultaneous block calculation of all three phenomena would have been theoretically preferable (strong coupling). In addition, severe limitations are expected on the size of the common time step (macro time step) since the characteristic time constants (values of $r$ given in parentheses) are spread over a large spectrum. To remedy this drawback special attention has been devoted to the development of implicit or semi-implicit algorithms in each module, allowing for large values of the macro time step $\Delta t$ (governing the whole core behaviour), which is of fundamental importance in large modular systems such as EAC. Special care is also necessary to avoid time-consuming iterations through the whole system in order to converge to unique values for the neutronic power $Q$ and the feedback reactivity $\rho$. As a matter of fact the system is highly non-linear so that a predictor-corrector procedure is required. The calculation of a time cycle typically starts with a guessed value $Q^0$ of the neutronic power: this in turn generates "guessed" values for the various thermal feedback reactivities which are entered in the neutronics module to determine a new value of $Q$, not necessarily identical to the predicted value $Q^0$ [1].
3. Selection of a Hydrodynamical Module

Of particular importance in the closed loop system of the whole core behaviour is the thermohydraulic "box", essentially for two reasons:

i) the voiding rate of the core generates a feedback reactivity \( \rho_{\text{ne}}(t) \) of positive value (the only one!) which is likely to make the whole system unstable (neutronic excursion);

ii) boiling may lead to clad dry-out and irreversible material melting (loss of nominal geometry).

Those two characteristic features should serve as guidelines to discern the fundamental aspects of sodium hydraulics in connection with LMFBR safety analysis. The importance of a parameter, such as the amount of superheat or the choice between heterogeneous and homogeneous boiling model for example, should be determined by the effect it has on the calculation of either the void reactivity or the clad temperature. Another choice which has to be made in this context concerns the modelling of the geometrical configuration of the core. Two approaches are indeed commonly used:

i) the porous model approach which homogenizes the whole core, usually in two dimensions \((r, z)\), defining therefore characteristic parameters which are based on a sometimes questionable simplification;

ii) the multichannel approach which considers concentric annuli of typical one-dimensional channels for which numerous experiments have long been providing the necessary physical data to cover not only sodium single- and two-phase flow but also fuel behaviour under various conditions.

Taking into account the above selection criteria, EAC has deliberately chosen the multichannel approach (see Fig. 2) in which each channel (see Fig. 3) is representative of one or more subassemblies undergoing a typical power distribution. As a result of its modular structure EAC is even able to select for each channel (up to 10) the most appropriate hydrodynamical module (up to 4), using any of the 3 available physical databanks. In this way EAC appears to be also a useful tool for intercomparison of physical models and numerical techniques.

Emphasis will be given now in particular to the hydrodynamical module EACMAND which is originally based on a French computer code called MANDRIN [2] which has been extensively tested against experiment. In this model the coolant is assumed to behave as a homogeneous single fluid obeying the three classical conservation equations of mass, linear momentum and total energy. A fourth equation, actually, is added to this set in case of boiling: this equation of state, which is of Differential type, accounts for the relaxation phenomenon which has been effectively observed in comparing the measured vapour quality to the theoretical equilibrium value. With \( u \) denoting the coolant velocity and \( X^* \) and \( X \) the real and the theoretical values, respectively, of the vapour quality this equation of desequilibrium reads as:

\[
\frac{\partial X}{\partial t} + u \frac{\partial X}{\partial z} = \frac{X^* - X}{\theta} \quad \text{with } \theta = \text{delay time}
\]

(1)

The four main variables are in fact: pressure \( p \), enthalpy \( h \), mass velocity \( Q \) and vapour quality \( X \). According to the classical Boussinesq approximation, the fluid is considered incompressible as long as it remains in single phase, that is: the mass density depends only on the temperature \( \rho_L = \rho_L(T) \) and \( \partial \rho_L / \partial p = 0 \) whereas it is taken in the boiling region as the usual mean value between vapour and liquid phase \( \rho_{2ph} \approx \alpha \rho_v + (1-\alpha) \rho_L \) with \( \alpha = \text{void fraction} \).

4. Realistic Boundary Conditions and Heat Source Terms

As a matter of fact the original MANDRIN code has been developed to describe typical out-of-pile experiments (i.e. without neutronic feedback) in electrically heated single pin geometries. This motivated the code developers to give the power profile (Watt/m) in input as a relatively simple time-dependent function and to prescribe the following boundary conditions in both steady-state and transient situations:

1) hydraulic conditions: at the inlet: either inlet mass flow rate as function of time or external pump characteristic

and at the outlet: specified pressure (usually constant value)

2) thermal conditions: or specified enthalpy and vapour quality

- at the inlet (if no flow reversal)

- at the outlet (if flow reentry)

In a realistic core model, however, one has to consider not only the presence of several channels in parallel, but also the existence of an external circuit (that is: an external characteristic) so that a new type of hydraulic
boundary conditions is required. In fact, a possibly time-dependent overall pressure drop has to be specified over the whole core (see Fig. 2), instead of a common value for the inlet mass flow rate. Further, as far as the thermal boundary conditions are concerned, nominal (that is: steady state) operation of the reactor requires the specification of the temperature at both in- and outlet of the core. As a consequence, the steady state value of the mass flow rate in each channel is determined according to a simple energy balance between the total heat produced in that particular channel and that convected away by the coolant. Since, on the other hand, the pressure is also specified at in- and outlet, the system is overdetermined in steady state, and an inlet throttling factor must be introduced for each channel to remedy the mismatch between calculated and specified pressure drop.

To account for realistic heat source terms care must be taken of the strong interaction which exists between the two "boxes", "thermohydraulics" and "fuel behaviour" of Fig. 1: a small deviation of the coolant temperature $T_M$ may affect drastically the power-to-coolant $q_G = q_C = h_m (T_C - T_M)$, and hence the clad surface temperature $T_C$ mainly in the vicinity of clad dry-out time when the value of the heat transfer coefficient changes abruptly (according to NUKIYAMA’s curve). Separating the clad from the fuel and introducing a simplified model of the clad within the hydrodynamic module helps a lot in describing correctly this skin effect: this new coupling mechanism between heat transfer module and thermohydraulics module is about as strong as the theoretical block solution of the two corresponding systems of equations [1].

5. ICE-type Finite Elements

Typical accident situations in nuclear reactor analysis may involve violent pressure gradients, followed by flow reversals at both channel ends, due to boiling or condensation, which in turn modify drastically the heat exchange properties between fuel pin and coolant. In such cases it is highly desirable to apply a well established numerical strategy, such as the ICE technique [3], within a versatile framework, such as the finite element method which allows for complex configurations and irregular mesh subdivisions.

The original ICE technique has proven to be applicable for all MACH numbers from zero (incompressible limit) to infinity (hypersonic limit). This property makes it a very attractive method to describe transient two-phase flow situations where the velocities typically may vary from very low values (in fact, such as before onset of ebullition) to very large values (characterized by violent slug expulsions). The crucial feature that enables this property is the advanced time (implicit) treatment of the physically most significant variable, that is the pressure in this case or the density in the classical applications of ICE.

The basic idea of ICE is to determine at each time interval the main variable using a Poisson type equation, from which the other independent variables are then derived. As this second order equation applies for the pressure in EACMAND, the problem of satisfying the in- and outlet boundary conditions on this same pressure field becomes a standard DIRICHLET type problem (essential boundary conditions involving only one extreme node). Other boundary conditions of the NEUMANN type are also implemented (natural boundary conditions involving more than one node at the extremities): examples are the prescription of inlet or outlet mass flow rate in function of time and the assigning of an external characteristic, i.e. the system pressure drop given as a function of the inlet mass flow rate.

Now, as far as discretization is concerned, one-dimensional finite elements are considered in space (2-dimension) with linear velocity fields and uniform pressure, enthalpy and vapour quality: the heat source distribution is also supposed to be element-wise uniform. As a result the discrete analogue of the momentum equation appears to be a balance equation of nodal forces written originally for each element independently of its neighbours, which may lead to significant advantages in the treatment of complex configurations, such as that of Fig. 3. Finite difference methods, on the contrary, tend to express the same equation of motion directly in terms of stresses (or pressures) taking into account for each cell one or even more neighbouring cells. On the other hand it has also been proven that finite elements reproduce quite well wave propagation properties in transient compressible fluid flow problems [4].

As no extremum principle exists for the general hydrodynamical equations, Galerkin’s method of weighted residuals is applied to formulate for each element a variational statement associated with the momentum equation and its boundary conditions, which is equivalent to the classical Principle of Virtual Power: virtual power of inertial forces $\sum$ of the virtual powers of internal + external forces. To derive the global matrix equation of the hydrodynamical system the principle of virtual power is then extended to the whole mesh by summing up the resulting equation over all finite elements with the power due to the discontinuities in pressures between elements omitted. Written directly in incremental form, the discrete momentum equation looks as follows after assembling at node $j$:

$$v_{j} \cdot \delta Q_{j} + S_{j} \cdot \delta p_{j} - S_{j-1} \cdot \delta p_{j-1} = v_{j} \quad \text{with} \quad 2 \leq j \leq N$$

(2)
where \( v_0 \) is a typical coefficient (dimension of a velocity), \( S_0 \) is the flow area which may vary over the channel length (se Fig. 3) and \( v_S \) is a source term; \( N \) is the total number of finite elements and the symbol \( \delta \) signifies the increment value between two successive iterations, \((K)\) and \((K+1)\), that is, \( y \) being an arbitrary function and index \( n \) denoting the time \( n \Delta t \):

\[
K+1, y^{n+1} = K, y^n + \delta y \quad \text{or} \quad \frac{\partial y^{n+1}}{\partial t} = \frac{K, y^{n+1} - y^n}{\Delta t} \quad \frac{\delta y}{\Delta t}
\]

(3)

if a forward (EULER) difference scheme is taken to integrate in time.

Similar expressions are further derived for the remaining quantities. Indeed the following equations are found in solving over each finite element the global conservation equations of mass, enthalpy and vapour quality:

\[
\begin{align*}
\text{Mass} & \quad r p_j \delta p_j + r h_j \delta H_j + r x_j \delta X_j + \delta Q_j + 1 - \delta Q_j = r s_j & 1 \leq j \leq N \\
\text{Enthalpy} & \quad h h_j \delta H_j + h p_j \delta p_j = h s_j & 1 \leq j \leq N \\
\text{Vapour quality} & \quad x p_j \delta p_j + x h_j \delta H_j + x x_j \delta X_j = x s_j & 1 \leq j \leq N 
\end{align*}
\]

(4) (5) (6)

The discrete analogue of the typical Poisson type equation can be written as follows for each node \( j \):

\[
t t_j \delta p_{j+1} + u u_j \delta p_{j+1} + v v_j \delta p_{j+1} = s s_j & 2 \leq j \leq N-1
\]

(7)

which has been obtained by elimination of the variables \( \delta Q, \delta H \) and \( \delta X \) from the system of equations (2), (4), (5) and (6). Note that the system of equations (7) is nothing but the typical symmetric tridiagonal matrix of the Laplacian operator - it loses however its symmetry when the flow-areas are not constant (\( S_j \neq S_{j+1} \)).

6. Results and comparative exercises

As a test it has been found useful to participate in a common Benchmark exercise involving sophisticated computer models which are currently used to compute hypothetical core disruptive accidents. Such a joint effort has been indeed undertaken under the coordination of the Commission of the European Communities by the Whole Core Accident Codes Group which is a subgroup of the Safety Working Group of the Fast Reactor Coordinating Committee. A LOF exercise has been proposed for which the basic assumptions (that is: core lay-out plus initial and boundary conditions) have been given in [5]. The EAC code, actually, participates in a more complicated exercise which has been proposed on the basis of the previous Benchmark problem. This makes it possible not only to compare EAC with other whole core accident codes but also to compare various hydrodynamical modules inside EAC itself. As a first result EACMAND and EACBLOW, which is based on the heterogeneous boiling model BLOW-3 [6], have shown to give nearly identical responses in single phase flow and only slightly diverging results in two-phase flow, as it is shown in Fig. 4. On the other hand, efforts have concentrated on the correct prediction of dry-out within the voided region, which requires special care as no film thickness is available in a homogeneous model - see Fig. 5. Larger discrepancies appear here in comparison with the heterogeneous model EACBLOW, but they are still acceptable according to the two criteria set up in Section 3. Finally, global results are presented in Fig. 6 which are of interest for those who are in charge of predicting the energetics coming out from such accidents: it is shown in particular that removal of sodium from the inner parts of the core adds significant amounts of reactivity so that the reactor may possibly undergo an energetic excursion.

As a conclusion it may be argued that phenomenological understanding in the field of LMFBFR technology has matured to the point where computer simulations of these systems are quite feasible and can provide sufficient insight into the problems associated with the initiating phase of hypothetical whole core accidents. Obviously a more detailed analysis requires the understanding of more sophisticated phenomena which are not yet satisfactorily dealt with in the current whole core accident codes, such as for example the dynamic flow redistribution and heat transfer effects between assemblies.
References
[1] Reyren, J., "Coupling of fuel-pin and thermohydraulic modules in computer programs for reactor core analysis", 7th Int. Conf. on Structural Mechanics in Reactor Technologw, paper C4/1, Chicago, USA, August 22 - 26, 1983.

FIG. 1 - THERMAL FEEDBACK EFFECTS IN THE NEUTRONIC BEHAVIOUR OF A LMFBR CORE
Fig. 2 CONCEPTUAL PICTURE OF LMFBR SIMULATION MODEL.

Fig. 3 - Typical geometry of an LMFBR subassembly (channel configuration)

**BOEC LOF COMPARATIVE EXERCISE**

**FIGURE 4** COMPARISON OF BLOW AND HANDIN AT BOILING INCEPTION
FIGURE 5 IN- AND OUTLET FLOWS + VOIDING AND DRYOUT PROFILES VS. TIME

FIGURE 6 STORED ENERGY AND REACTIVITIES VS. TIME