COMETA/SEURBNUK-EURDY: A Coupled Code for Prediction of Reactor Vessel Response due to Fuel Coolant Interactions

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ABSTRACT

In order to calculate structural deformations that may be caused by a steam explosion in water-cooled reactor prototypical accident conditions, the thermal-hydraulic fuel-coolant interaction code COMETA is being coupled with the hydrodynamic/structural code SEURBNUK-EURDY. Initially, a very basic off-line coupling scheme has been adopted in view of introducing a more complex on-line scheme. The two separate codes and the simple coupling mode are briefly described. Application of the combined code to the KROTOS 44 experiment characterised by a super-critical steam explosion is presented. Pressure predictions and measured results are in reasonable agreement.

1 INTRODUCTION

Active modelling is currently underway in several research centres to investigate Fuel Coolant Interactions (FCIs) with particular emphasis on the different stages of premixing, triggering, propagation and expansion. In order to validate these models, fundamental experimental investigations are being performed in the FARO and KROTOS test facilities at JRC, Ispra [1, 2]. These experiments are aimed at providing detailed benchmark data to examine the effect of fuel-coolant mixing conditions on explosive energetics with both simulant materials such as alumina and prototypical core material under controlled conditions.

In order to analyse FCIs in the experiments conducted in the FARO and KROTOS facilities, the computer code COMETA (Core Melt Thermal Hydraulic Analysis) [3] has been developed at JRC, Ispra. The original objective of this code was the prediction of system thermal-hydraulic behaviour in the FARO test facility for design verification, definition of operational procedures, and test interpretation. COMETA is at present being developed to include also a steam explosion model, IDEMO [4], to analyse the explosion phase in a FCI sequence. Although COMETA has proved to be a very useful tool in FCI analyses, it does lack the possibility to predict structural deformations, an essential requisite in nuclear power plant safety studies if a Hypothetical Core Disruptive Accident (HCDA) is assumed to occur.

To address the problem of predicting structural deformations under best-estimated void and pre-mixing conditions as calculated by COMETA, the use of the computer code SEURBNUK-EURDY [5] has been considered. SEURBNUK uses an Eulerian finite difference scheme to compute the motion of a compressible liquid enclosed within a moving...
structural boundary whose motion is computed by the finite element code EURDY. Both SEURBNUK and EURDY, as stand-alone programs, are well validated from participation in past international code comparison exercises such as COVA [6]. The coupled code SEURBNUK-EURDY was extensively used in support of fast reactor safety studies, which included the CDFR and SNR-300 designs [5, 7] to represent both pool- and loop-type concepts.

In the past, most SEURBNUK-EURDY reactor calculations modelled the zone where expanding vaporised core products were assumed to form as a homogeneous high-pressure gas bubble. However, this model might not be sufficiently adequate for an FCI because the actual development of the reaction zone in time and space is not taken into account. Since the code COMETA models the development of FCI reaction zone, the two codes COMETA and SEURBNUK-EURDY are coupled together. In brief, data computed by COMETA describing the state of the reaction zone before the explosion is supplied to SEURBNUK-EURDY and thus the heterogeneity of this region is taken into consideration. Finally, the code SEURBNUK-EURDY is used to predict the shock wave propagation and response of the containment vessel due to the FCI.

The coupled code is only in its initial state of development. Nevertheless, in order to demonstrate the status and usefulness of the coupling of the two codes some initial results will be presented concerning a KROTOUS experiment [8] in which a strong steam explosion occurred.

2 CODE DESCRIPTIONS

2.1 The COMETA Code

The COMETA (Core Melt Thermal-hydraulic Analysis) code [3] is an integral system code coupling thermal-hydraulic and melt fragmentation modules for the simulation of FCI and quenching. It has been specifically developed to provide a computational tool for FARO test design and specification, definition of operational procedures and experimental test analysis.

The motion of the two-phase fluid flow is described by separate mass, momentum and energy conservation equations for the liquid and vapour phases, plus a mass conservation equation for each non-condensable gas included in an Eulerian control volume. The melt (fuel) field that flows through and mixes with the two-phase field is described by using Lagrangian coordinates.

The two-phase field is organised as a number of lumped volumes connected with junctions. A 2-D nodalisation can be built up by connecting a number of macro-volumes (containing an arbitrary number of radial and axial volumes) with macro-junctions. In addition, thermal-hydraulic components such as valves, separators, pumps and accumulators can be defined in order to represent the integral configuration and related transient response of the simulated facility.

Jet, droplets, and debris components describe the melt field. The melt is released in the form of a jet that becomes conical in shape. Three models for jet fragmentation and erosion are included: the original COMETA model based on the Jet Breskup Length criterion (L/D is evaluated at each time step providing the local erosion rate), the Corradini-Tang model included in the TEXAS code [9] and the IKEJET model developed by the University of Stuttgart [10].

At present COMETA does not have a steam explosion model, but the IDEMO model [4] will be available in the near future.
2.2 The SEURBNUK-EURDYN Code

SEURBNUK-EURDYN is a 2-D, axisymmetric, computer code capable of performing hydrodynamic/structural mechanic calculations and was originally written with the aim of assisting in the evaluation of fast reactor containment integrity after a HCDA. The reactor coolant is modelled as a compressive fluid and an implicit finite difference algorithm similar to ICE [11] computes its motion. A complementary structure calculation taking into account material and geometrical non-linearities is performed to simultaneously compute the deformations of the various internal plates and shells that may be perforated, and the main tank. Representation of massive internal structures is provided by means of the EURDYN-link [12]. fluid/structure interaction effects are included.

In a typical reactor configuration related to an HCDA the fluid will enclose a gas bubble representing the expanding vaporised core products and the fluid upper surface will be in contact with the cover gas blanket. As the core bubble expands the reactor fluid is driven upwards. If the cover gas gap closes up sufficiently to bring the fluid in contact with the underside of the reactor roof then the code will compute the high impact pressures generated at contact. The motions of Lagrangian marker particles that define free surfaces are estimated by extrapolation from pairs of mesh velocities in the neighbouring coolant velocity field.

Although the program was primarily written for HCDAs in fast breeder reactors, it can also be used, possibly with some modifications, to model other 2-D configurations. The major modifications to produce the partially coupled COMETA/SEURBNUK-EURDYN code include:

- Add a two-phase equation of state for water/steam mixtures in thermal equilibrium.
- Modify the input subroutines to accept the COMETA output data concerning the FC.
- Modify the internal energy calculation to include energy deposition from the fuel.

3 DESCRIPTION OF THE KROTOS FACILITY

Fig. 1 shows the main components of the KROTOS test facility: the radiation furnace, pressure vessel and test section. The furnace, maximum power 130 kW, consists of a cylindrical tungsten heater that encloses the tungsten crucible containing the melt material, Al₂O₃. After having reached the desired melt temperature the crucible is released from the furnace and falls by gravity through a 4 m long release tube. A rapid-acting slide valve halfway down the tube closes after the crucible has passed and isolates the furnace from the test section below.

During its fall, the crucible breaks a copper wire that generates the zero-time signal for the data acquisition system. On arrival at the bottom of the release tube the crucible impacts onto a conical shaped puncher that breaks the bottom of the crucible and allows the melt to pour into the test section via a funnel with an exit diameter of 30 mm.

The lower part of the KROTOS facility consists of a test section bolted to lugs welded on the inner walls of a

Fig. 1 - KROTOS Test Facility
pressure vessel, both components are made of stainless steel. The pressure vessel, inner diameter 0.4 m, height, 2.21 m, designed for 2.5 MPa at 493 K, has a thick flat bottom and a flanged flat upper head. The strong test section, inner diameter 200 mm, outer diameter 240 mm, can be closed by either a flat plate or with a gas trigger device.

The gas trigger, chamber volume 15 cm³ can be charged to a pressure of up to 20 MPa (argon) and is closed by a 0.1-0.25 mm thick steel membrane. After melt penetration down to the lower region of the test section, the mechanical destruction of the membrane causes a pressure pulse to propagate vertically upwards and interact with the melt-coolant mixture. The gas trigger device is activated either by a specific thermocouple signal or by a backup time delay circuit.

Pressures both in the test section (K0-K5) and pressure vessel (C1-C3 and C11-C13), temperatures and water level swell histories are the main experimental parameters measured in every test.

4 KROTOS 44 EXPERIMENT

Six KROTOS experiments (KROTOS 38 to 44) were performed to study premixing of molten alumina in near saturated (KROTOS 41 and 44) and sub-cooled water (KROTOS 38, 40, 42 and 43) conditions. In the case of a spontaneous or external trigger, the propagation and expansion phase of the steam explosion was also studied. The test section was closed by a flat bottom plate in all experiments except for KROTOS 38 and 44 in which a gas trigger was employed. Supercritical steam explosions occurred in all but one experiment (KROTOS 41). More details of the main results are described in reference [13].

The KROTOS experiment considered here is KROTOS 44. The geometry of the KROTOS vessel, as shown in Fig. 1, and described in section 3. The discharged melt, mass 1.5 kg, temperature 2673 K, initial diameter 30 mm, falls a distance 0.44 m before impacting with the water. The coolant, mass 32.9 kg, height 1.105 m, has an initial temperature 363 K (10 K subcooling). A gas trigger was fitted and was activated 1702 ms after the breaking of a thin copper wire stretched across the release line, halfway down. On activation, the gas trigger (initial pressure 14.8 MPa, volume 15 cm³) sends a shock wave from the bottom upwards through the coolant and produces an escalating steam explosion. The pressures measured at the pressure transducers are shown in Fig. 5. From these experimental results it appears that the steam explosion commenced somewhere between pressure transducers K1 and K2. It can be confirmed from water temperature measurements that the melt jet arrived at gauge TC2, the same height as the pressure transducer K2.

4.1 COMETA Premixing Calculation

The KROTOS geometry was modelled with the 1-D version of the COMETA code and Fig. 2 shows the simplified nodalisation. The test vessel diameter (0.2 m) is correctly modelled. Although the upper region does not describe the actual geometrical configuration, it does take into consideration the whole volume of the cover gas present in the pressure vessel. The melt jet is introduced at the upper edge of cell number 27 with an initial velocity of 9 m/s. On entering the coolant the jet commences to fragment and the calculation is allowed to continue until time 1.5 s (equivalent to the experimental triggering time, 1.702 s). The positions of the groups of melt particles at time 1.5 s are indicated as circles in Fig. 2, the radius of the circle being proportional to the total weight in the group. The fractions of water and vapour in an Eulerian cell are shown as black and grey shaded areas, respectively.

In order to continue the calculation on SEURBNUK-EBURDY, axial distributions of pressure, water/vapour quality, and melt mass were downloaded to a file to be read as input.
data for the code SEURBNUK-EURDYNE. The vapour void fraction and melt mass distributions are presented graphically in Fig. 3.

This method of coupling is simple; however, it is only intended to be a temporary solution in order to demonstrate that data from the two codes can be interchanged.

Fig. 2 - COMETA Nodalisation

Fig. 3 - Vapour Void Fraction, Melt Mass Distribution

4.2 SEURBNUK-EURDYNE Steam Explosion Calculation

Fig. 4 shows the SEURBNUK-EURDYNE nodalisation for the KROTOS 44 test section. Here, it is not necessary to model the whole pressure vessel because only the response of test section is required. The duration of the principal events, the steam explosion and subsequent shock propagation are very brief, about 5 ms. During this time all the major deformations, if any, will have taken place. The pressure in the cover gas is low compared with the shock pressures and the time to compress it is long compared with 5 ms, thus it is not necessary to model the entire cover gas.

Eulerian meshes have dimensions $\Delta r = \Delta z = 0.01$ m, in order to adequately resolve the trigger. Axisymmetric thin-shell elements are used to model the cylindrical wall, internal radius 0.1 mm, thickness 0.02 m. All thick structures (vessel base, flanges, trigger, conical insert) are assumed to be lumped together as one structure and modelled using axisymmetric triangular elements. The elastic-plastic material properties of the test vessel are described by a tri-linear stress-strain relationship (Young's modulus $1.86 \times 10^9$ Pa, elastic limit $2.35 \times 10^9$ Pa, first hardening slope $3.72 \times 10^9$ Pa.) The equation of state for the steam-water is a two-phase equation specially developed at JRC, Ispra to cope with a supercritical steam explosion [14]. The trigger is modelled as a high-pressure gas bubble having a simple pressure-volume relationship, $P = P_0 \cdot \gamma^\gamma$, where $P_0$ is the initial pressure, 14.8 MPa, $\gamma$ is the specific volume and $\gamma = 1.4$.

The SEURBNUK-EURDYNE calculation was initiated by reading the data produced by COMETA describing the axial distribution of pressure, steam-water quality and melt mass, at the time when the trigger was activated. Here, it is assumed that the radial distribution is homogeneous. Knowing the values of pressure and quality, consistent values of internal energy and density are calculated using the two-phase equation of state for steam-water. The melt mass distribution is used to indicate that a thermal energy source term exists in a particular Eulerian cell and its magnitude is a function of the melt mass. However, the actual physical presence of the melt and its motion are not taken into consideration.
The high pressure in the trigger produces a shock that propagates upwards through the water-steam-melt mixture. When this shock wave arrives in an Eulerian containing some melt the program checks to see the pressure in the cell is greater than 5 MPa, if so, then additional energy is deposited in the cell and the thermodynamic variables recalculated. In order to demonstrate that the numerical scheme is functional, a simple internal energy source term was chosen, $\dot{e}_i = k \cdot m \cdot d t$, where $\dot{e}_i$ is the specific internal energy (J·m$^{-3}$·kg$^{-1}$), m is the melt mass (kg), $d t$ is the calculation time-step (s), and k is constant ($12.0 \cdot 10^9$ W·m$^{-3}$·kg$^{-2}$). The value of k was chosen after a few trial runs.

In Fig. 5 the pressures predicted by the code at gauges K0 to K5 are compared with experimental values, the code predictions are quite good. The computation failed at 1.94 ms due to bubble interface configuration difficulties, a specific problem associated with the poor definition of the trigger on the underlying Eulerian grid. Nevertheless, the pressures predicted
at gauge K0 follow well the experimental values up to 1.5 ms. At about 1.5 ms it was necessary to temporarily freeze the position bubble interface in order to allow the calculation to continue. The code requires modifying in order to deal with a bubble volume smaller than an Eulerian cell. Predictions at gauges K1 and K2 are also quite good, however, the experimental curves indicate that the actual position of the melt jet front was probably a little higher than that predicted by COMETA. The predicted arrival times of the shock wave at gauges K4 and K5 are late, most probably indicating that the vapour void fractions predicted by COMETA are overestimated above gauge K3.

Visualisation of pressure field during the development of the computation reveals how the explosion propagates upwards while shock waves also propagate downwards and recompress the trigger-gas. Further expansion of the trigger-gas at about 1.5 ms produces a shock wave that propagates upwards. The upward propagating explosion front first has to substantially lower, or squeeze up, the vapour void fraction in the Eulerian cells ahead of it before any appreciable pressure growth is observed in them, a mechanism often described as the snowplough effect. The presence of the cover gas interface has also a very important role because the pressure waves arriving at this interface are reflected downwards as rarefaction waves that gradually erode the high pressures generated within the water column.

In the case of experiment KROTOS 44, the strains are very small (maximum hoop strain \(-0.01\%\) at position K1) and are well within the elastic range. However, this does not signify that the inclusion of thick structures has not affected the results. In the COVA code validation exercise [6] it was shown that thick structures absorb energy and release it a short time later thus modifying the pressure/time histories during the fluid-structure interaction.

5 FUTURE DEVELOPMENT

At least two main options are available to couple COMETA with SEURBNUK-EURDYNE.
1. Pass the water-vapour-melt premix conditions predicted by COMETA to SEURBNUK-EURDYNE for the computation of the whole explosion and vessel response sequence.
2. Calculate the explosion using COMETA with IDemo, pass the pressure data close to structures to SEURBNUK-EURDYNE; calculate and feedback the vessel displacement data to COMETA; include the effect of modified boundary position in COMETA.

Of these two choices, the first is more attractive because a well-proven fluid-structure interaction mechanism for curved boundaries already exists in SEURBNUK-EURDYNE. It would be necessary to include a model that calculates the thermal energy exchange between the melt and coolant during the explosion.

The second choice is less attractive because the data exchange between the two programs is significantly greater and the fluid-structure interaction algorithm would need re-validating. However, the potential of the IDemo two-phase, non-equilibrium model seems more attractive than the SEURBNUK two-phase, equilibrium model. Another drawback is that COMETA does not model curved boundaries in the same manner as SEURBNUK-EURDYNE.

A final choice has not yet been taken, but the first option will be examined first. Hence, a more satisfactory explosion model must be incorporated in SEURBNUK-EURDYNE and the predictions compared with reliable experimental data (e.g. the KROTOS experiments). Both triggered and spontaneous explosions in 2-D geometries will be considered, making use of the 2-D option in COMETA.
6 CONCLUSION

In principle, it has been shown that coupling of the two codes is possible, albeit very simple in this case. For experiment KROTOS 44 the agreement between pressure predictions and experiment is generally quite good. Some differences in the stock propagation speeds were present in the upper half of the water column, probably due to differences in vapour void fractions. All test section vessel strains were small and well within the elastic range.

Further modifications are necessary to model more correctly the exchange of thermal energy between the melt and coolant during the explosion. Future developments include two possible strategies for coupling; advantages of the two methods have been briefly outlined.

7 REFERENCES