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GEYSER/TONUS : a coupled multi-D lumped parameter code for reactor thermal hydraulics analysis in case of severe accidents

M. Petit, M. Durin*, J. Gauvain
Commissariat à l'Energie Atomique
DMT/SEMT/TTMF
91191 Gif sur Yvette Cedex
France

ABSTRACT

In many countries, the safety requirements for future light water reactors include accounting for severe accidents in the design process.

As far as the containment is concerned, the design must now include mitigation features to limit the pressure and temperature inside the building. Hydrogen concentration is also a major issue for severe accidents.

In this context, new needs appear for the modeling of the thermal hydraulics inside the containment. It requires the description of complex phenomena such as condensation, stratification, transport of gases and aerosols, heat transfers. Moreover, the effect of mitigation systems will increase the heterogeneities in the building, and most of those phenomena can be coupled, as for example hydrogen stratification and condensation.

To model such a complex situation, the use of multi-dimensional computer codes seems to be necessary in case of large volumes. The aim of the GEYSER/TONUS computer code is to fulfill this need. This code is currently under development at CEA in Saclay. It will allow the coupling of parts of the containment described in a lumped parameter manner, together with meshed parts.

Emphasis is put on the numerical methods used to solve the transient problem, as the objective is to be able to treat complete scenarios. Physical models of classical lumped parameters codes will adapted for the spatially described zones.

The code is developed in the environment of the CASTEM 2000/TRIO EF system which allows, thanks to its modular conception, to construct sophisticated applications based upon it.

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* Presently at : Commissariat à l'Energie Atomique, IPSN/DPEI, CE Fontenay, BP 6, 92265 Fontenay aux Roses Cedex, France

INTRODUCTION

The first studies of PWR containment behavior during a severe accident were performed in the seventies. At that time, the main objective was to insure that no significant release of fission products could occur during and after a core-melt accident. Then, containment structure studies required the knowledge of the mechanical loading, that is the evolution with respect to time of the mean pressure and the mean temperature of the internal atmosphere. These evolutions were computed by codes developed with a «single node» approach based on a global mass and energy balance. In this category, one can find, for example, the CONTEMPT-LT [1] or MARCH2 [2] codes. This approach was sufficient because of the main characteristics of concrete containment (high thermal inertia and low thermal leakages) and because thermal exchanges are very efficient in case of steam condensation.

During the eighties, hydrogen risk became more and more a concern. Then, modeling activities have gone in two directions. On the one hand, multi-compartment codes have been developed, based on the previous approach with additional coupling relationships between compartments. Examples of those codes are CONTAIN [3], JERICHO [4], MAAP [5] or RALOC [6]. This approach give good results with respect to pressure evolution, but it underestimates the possible stratifications and is also sensitive to the domain nodalization.

On the other hand, general purpose multi-dimensional codes were used for solving mass, energy and momentum equations with a spatial discretization. In this category one can find codes as GASFLOW / HMS [7] and GOTHIC / WGOTHIC [8]. This approach yields good representation of stratification in large volumes but typically requires very large computation times.

Lumped parameter codes are still likely to be used for safety analysis. But mechanistic codes will be more and more required in order to justify some assumptions made in studies performed with lumped parameter codes. With this objective in mind, CEA/DMT as undertaken the development of a coupled multidimensional and lumped parameter code named GEYSER/TONUS.

PHYSICAL MODELS

There are different physical models to be included in the code in order to have a good representation of the phenomenons involved in the evolution of the containment atmosphere in case of a severe accident. These models are listed below.

For all the physical models presented, the computations can be carried out either in 2D or 3D.

Compressible two-phase flow

The main model to implement in the code was for computing flows composed of steam with non-condensable gases (air, hydrogen, ...). The model must be able to treat compressible flows because of the injection of mass inside the containment (essentially

steam and hydrogen) which leads to a general raise in the pressure. It is also expected that the pressure level in the containment will remain quite low (typically less than five bars in French PWRs). Thus, apart from the condensate on walls and inner structures, only a very limited amount of water will exist as a liquid phase. If mass condensation is willing to occur, the droplets will be of micrometric size and will follow the gaseous flow. These arguments have driven us to choose a homogeneous model for representing the compressible two phase flows.

In the present model, the gases are assumed to be perfect (state equation). The physical parameters of the mixture depends on the composition but not yet on the temperature.

Turbulence is accounted for by a constant eddy viscosity, but it is planned to incorporate, in a near future other turbulence models, in particular a K-ε model.

An implicit time integration scheme had been developed in order to be able to treat long transients.

Condensation on walls and structures

The mass transfer by condensation on walls is modeled using the Chilton-Colburn approach and an analogy between heat and mass transfer. The computation procedure is then the following :

- The heat exchange coefficient by convection is calculated using a semi-empirical correlation on the Nusselt number Nu [9] :

$$Nu = 3.656 + 0.021\ Pr^{0.6}\ Re^{0.8}$$

- Using the analogy between heat and mass transfer, the Sherwood number Sh is written as [10] :

$$Sh = 3.656 + 0.021\ Sc^{0.6}\ Re^{0.8}$$

- The mass condensation rate j_s is evaluated by the following expression :

$$j_s = \frac{\alpha}{D} Sh(\rho_v - \rho_{ve}(T_w))$$

- The heat flux rate by condensation φ_c is then :

$$\varphi_c = j_s L$$

In these expressions, Pr is the Prandtl number, Re is the Reynolds number, Sc is the Schmidt number, α is the vapor diffusion coefficient, D is the containment diameter, ρ_v is the vapor density, $\rho_{ve}(T_w)$ is the density of the saturated vapor at the wall temperature and L is the latent heat of phase change.

Spray

An important mitigation system used in containment buildings is the spray system. The main characteristic of such a system is to bring a great amount of water in a liquid phase inside the containment building. Due to the sizes of the droplets being generated (roughly between 100 and 1000 μm) , the homogeneous two phase flow model is not adequate for modeling such an event. Rather, it is important to take into account the difference

between the movements of the gaseous phase and of the liquid phase. For these situations, a two fluid model has been developed. The formalism used for deriving the equations is as exposed by ISHII [11].

In this formulation, the first fluid is composed of the gases (vapor and non-condensibles) plus the small droplets generated by mass condensation if any. This fluid is the same as the one described by the model for compressible two phase flows. Fluid number two is the collection of droplets generated by spray.

For the mixture, the supplementary assumptions as compared to the homogeneous model are the following :

- if present, the small droplets generated by mass condensation are not affected by the spray droplets ;
- the volume fraction of the mixture is equal to unity, because the volume fraction of the spray droplets is always less than 0.001.

For the spray droplets, the main assumptions are :

- the droplets do not interact with one another ;
- the temperature is uniform inside a droplet and is equal to the interfacial temperature ;
- when injected in the computation domain, all the droplets have the same size ;
- the viscosity is neglected compared to inertia.

With this model, condensation can occur on the droplets, and their size is computed. For each fluid, local conservation equations for mass, momentum and energy are solved. Also added are equations for the conservation of water and for the volume fraction of the droplets. Thus, a total of eight partial differential equations are solved, with additional constraints being the state equation for both the vapor and air. For each non-condensible gas to be added in the computation (for example hydrogen), another conservation equation is to be solved in addition to the previous ones.

When deriving the complete set of equations, heat, momentum and mass transfer terms appear. They are detailed below.

Mass Transfer : The mass transfer is generated by condensation of vapor on the droplets. The model used is a Chilton-Colburn approach as described above, but in this case droplet Nusselt number Nu_{dro} is evaluated as [12] :

$$Nu_{dro} = 2.0 + 0.6\, Pr^{1/3}\, Re_{dro}^{1/3}$$

with $Re_{dro} = \dfrac{D|V_{mix} - V_{dro}|}{\nu}$ the Reynolds number of the droplets, D the diameter of the droplets, V_{mix} the velocity of the mixture, V_{dro} the velocity of the droplets, ν the kinematic viscosity of the mixture.

Momentum Transfer : The momentum transfer is the result of friction of the gas on the droplets. Assuming that the shape of the droplets is spherical, the drag force F_d is expressed as [13] :

$$F_d = C_d \frac{\pi}{8} \rho_{mix} D^2 |V_{mix} - V_{dro}| (V_{mix} - V_{dro})$$

with C_d the friction coefficient being $C_d = 24\left(0.1103 + \frac{1}{\sqrt{\mathrm{Re}_{dro}}}\right)^2$.

Heat Transfer : The heat transfer is the sum of two contributions. The first one is due to convection and is computed using the Nusselt number Nu_{dro} correlation. The second term is the result of condensation on the droplets and is calculated as for condensation on walls.

Other models

To complete the description, other physical models are to be included in the capabilities of the code.

For some of them, a first version has already been included in the TRIO-EF code [14, 15]. This is the case for **aerosols transport** [16]. Two approaches have already been investigated. In the first one, the Navier-Stokes equations are solved for a gas mixture. Then, a velocity field is computed for aerosols which is a combination of the gas velocity, the particles weight and the Stokes drag force. Aerosols concentration is calculated by solving a convection-diffusion equation, using a turbulent dispersion coefficient for the particles. The second approach consist in applying a two fluid modeling in a similar manner to what was done for spray. Work as also been performed on wall laws for aerosols deposition in a turbulent flow.

As far as **thermal radiation** is concerned, intensive work has been done in the past to model this phenomenon in transparent media [17]. For the last few years, focus has been put on modeling thermal radiation in participating media. This model is relevant for the containment because the atmosphere contains vapor and particles. Thermal radiation can possibly modify the flows if high temperatures are reached, for example in case of hydrogen combustion.

The chosen approach rely on a spherical harmonics decomposition with a P1 approximation. This method as proved to be efficient for coupling radiation equations with other conservation equations (momentum equation in the case of the containment) [18]. In a first phase, the radiative properties will be considered constant and will be determined by correlations as in the CONTAIN code. Then, if necessary, the model could be extended to take into account the spectral variation of the radiative properties, using the «Weighted Sum of Gray Gases» method.

Other models as **combustion** and **engineered safety systems** are currently under development. The work is also ongoing for both multi-D to 0-D and lumped parameter types of elements. For the latter, the physics included is not expected to be different from what already exist in the JERICHO code on which DMT as already worked in the past.

CODE CONSTRUCTION AND STRUCTURE

One of the main characteristics of the containment modeling under severe accident conditions is to couple different physical phenomenons of various nature, as for example turbulent convection, thermics, aerosols transport, combustion, ...

We also wish to be able to couple different types of spatial discretization :

- multi-dimensional for large volumes ;
- nodes for compartments.

These two constraints imply to develop original algorithms. This in turn induces to achieve a modular and versatile conception of the software. Also requested are advanced capabilities in terms of language for manipulating data structures and implementing algorithms logic.

We chose to use CASTEM2000 [19] and its user data manipulating language called GIBIANE. The code has an object-oriented conception. One can manipulate *objects* (data) by applying to them elementary operations defined in *operators* which are independent from one another. Examples of operators are matrices construction, linear system resolution and so on. Some operators implement loops and test conditions. They are used to build algorithms such as time integration of the spray model.

The development of the physical models described above have then been carried out in two phases. The first phase was the transcription in CASTEM2000 of thermal hydraulics of TRIO-EF. This phase provided basic operators for computing flows. The second phase consisted in the writing of algorithms for two phase flows, condensation or spray.

The advantages of this structure are the following :

- it is possible to develop in parallel different physical models in different, independent operators with a specified interface (objects read, objects written) ;
- it is easy to develop and test rapidly new algorithms written with the help of the data language ;
- the user has the ability to redefine operators, in order, for example, to test the effect of different correlation.

This allowed us to build, in a limited amount of time, tools for computing complex flow situations.

Finally, CASTEM2000 gives the possibility to encapsulate the algorithms in generic data sequences called *procedures*. These procedures present to the user a simplified interface with only a limited number of parameters to define. The GEYSER/TONUS code consists in a set of procedures dedicated to the containment modeling.

CODE VALIDATION

The validation of the code can be divided in several steps. The first step will be to validate the lumped parameter part. This will be achieved by comparison to other already qualified codes that use the same approach, for example JERICHO or CONTAIN. The second step is to validate the multi-dimensional part on analytical tests. There already

exist in the literature results for the different physical processes (condensation, combustion, ...). Then, the last step is to validate the code in a global manner, in particular the coupling of the different phenomenons. Global tests, at large scale, have already been performed (Battelle, HEDL, HDR, NUPEC). They are suitable for verifying only mean values, because they are not heavily instrumented and because the boundary conditions are not always well known.

Between both types of tests, there is a need for medium scale experiments with well defined boundary limits and with an instrumentation designed to assist in the modeling and validate this modeling. CEA/DMT has proposed to build an experimental facility called MISTRA [20] to fulfill this need for medium scale experiments.

APPLICATIONS

An application of the code has already been performed on a typical severe accident situation. The aim of the computation was to evaluate the evolution of the atmosphere in the free volume of a 900 Mwe PWR containment after a small break LOCA. This application is discussed in details in a companion paper presented at the same conference [21].

An extended presentation of the spray model applications have already been presented elsewhere [22].

In this paper, we will only present an application about the dynamic effect of spray on a stratification.

The studied geometry is that of the large dry volume of a 900 MWe PWR. It is 44 meter large and the maximum height is 36 meters. The computation domain is composed of about 2000 elements and the computations are carried out with a 2D plane model. There is a vertical symmetry plane so only one half is represented. The computation is isothermal.

It is assumed that there is a spray system of length 3.4 meters located at the top of the building on the symmetry plane. The diameter of the spray droplets is 500 μm. They are injected with a velocity of 2 m/s.

The atmosphere is initially composed of air at the bottom and a mixture of 44% air, 47.5% vapor and 8.5% hydrogen at the top. There is a stratification front located at an elevation of about 20 meters (see figure 1a). The atmosphere, initially at rest, is at 3 bars pressure.

After 35s (figure 1b), there is little interaction between the two zones. mixing is more efficient in the upper part (lighter gas) than at the bottom.

After 180s (figure 1c), there exist a jet of light gas that start from the top and goes to the bottom. The mixing now reaches also the heavier gas initially at the bottom.

After 270s (figure 1d), a general recirculation has taken place inside the containment, and the gases tends to become quasi homogeneous.

CONCLUSION

The basic physical models of the GEYSER/TONUS code have been presented. It is already possible to compute flows in reactors containment under severe accident conditions. Thanks to a spatial discretization, precise local informations can be obtained, in particular for hydrogen concentration which is a major concern nowadays. By use of an implicit method, the calculation of long transients can be achieved at a reasonable cost.

Further steps in the development will include improvements in the existing models, implementation of new ones for other phenomenons, and validation on both separate effects and global tests. The user interface will also have to be improved.

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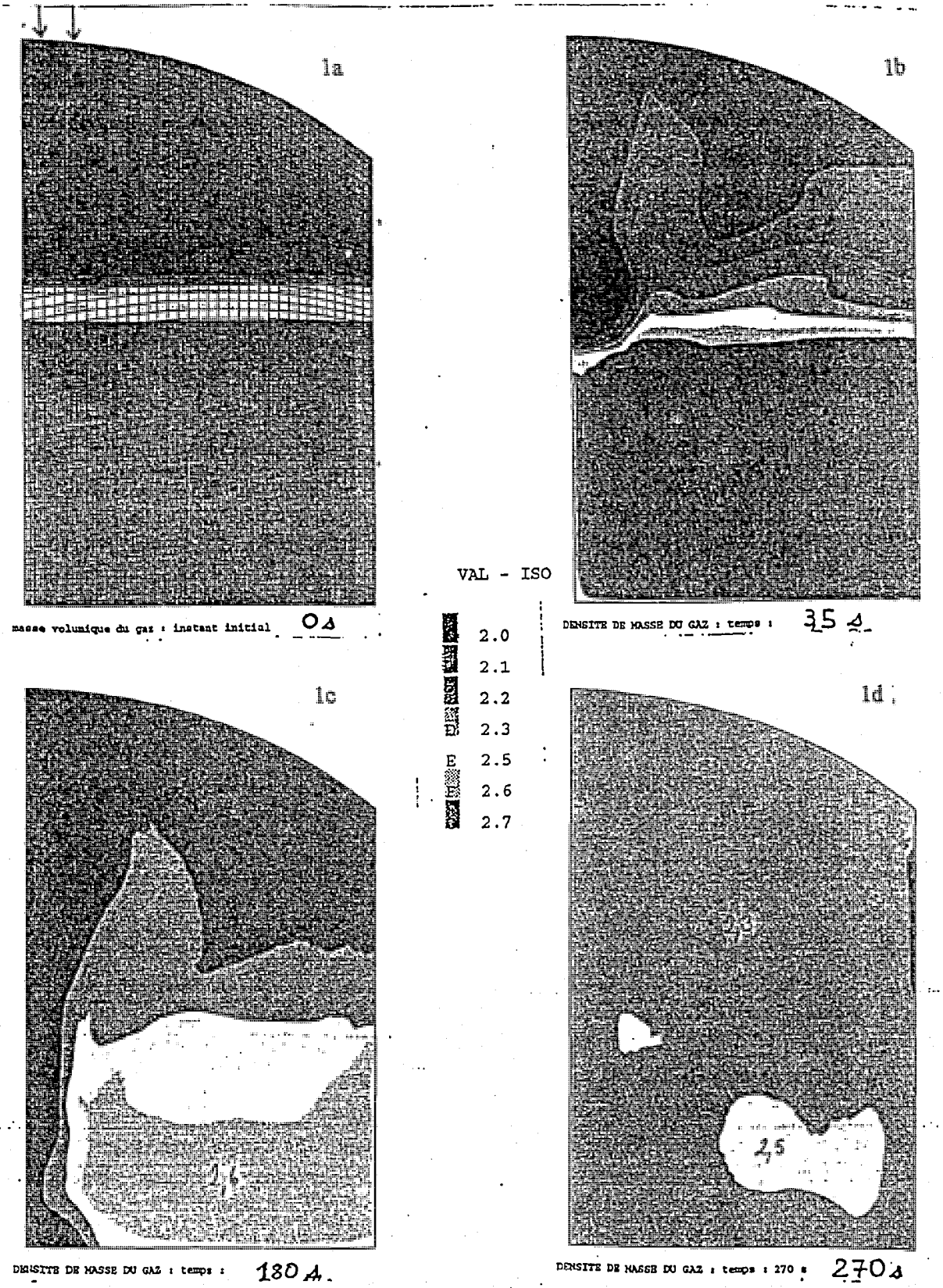
droplets



DENSITY IN THE CONTAINMENT AT DIFFERENT TIMES