THE USE OF PB-BI EUTECTIC AS THE COOLANT OF AN ACCELERATOR DRIVEN SYSTEM

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Abstract

The use of the Pb-Bi eutectic appears necessary for designs of spallation targets for ADSs. Even in ADS facilities cooled by gas, the target unit for the system contains lead-bismuth. Including this liquid metal as the primary coolant of the sub-critical reactor has important advantages in the safety field. Natural circulation, which can be enhanced by inert gas injection, avoids mechanical pumps or electrical induction pumps. Calculations made with CFD codes show that Pb-Bi coolant circulation by buoyancy forces is an important safety aspect. Even in the case of a loss of the heat sink, the core is still coolable with passive devices such as a Reactor Vessel Auxiliary Coolant System. Results from two different codes demonstrate similar conclusions about this passive emergency cooling system.

1. Introduction

The Nuclear Engineering and Fluid Mechanics Department in the Engineering School of Bilbao, is working on computational capacity of CFD codes, concentrating the efforts on liquid metals thermohydraulics. There is also a support of calculations of radiological protection, dosimetry, and shielding.

At the Joint Research Centre of the EC at Ispra (Italy), the ISIS group is doing calculations of an ADS prototype designed by ANSALDO [1]. A 2-D representation of this design has been set-up using the Computational Fluid Dynamic (CFD) STAR-CD code. Including the core, a riser cylinder and a heat exchanger in the upper part of the downcomer, as well as a gas plenum on top of the fluid. The vessel, the safety vessel around this one, and the reactor vessel air coolant system (RVACS) are also modelled.

The collaboration of these two groups led to the setting up of the FLUENT code for a similar representation of the ANSALDO's facility as the STAR-CD one. And the main objective of the calculations was to compare both codes, and see if they led to the same conclusions.

Using normal operation parameters, the model was driven to a steady state situation. And then, it was supposed to come in a situation of a station blackout to see the behaviour of the Pb-Bi eutectic flowing in natural convection.

This benchmark work, not yet finished, will lead to a better comprehension of the behaviour of the codes, and to propose possible modifications of some of the models. On the other hand the detailed study of the comparison results will help to achieve a better design for the demonstration facility.

In this paper some first FLUENT calculations are shown together with the STAR-CD ones, and it can be said that results are not that different, taken into account that two different codes were used and two different persons were doing the calculations.

2. Description of the accident

The description of the ANSALDO's prototype design is fully explained in [1], but apart from the steady state calculation based on this normal operation design, it is important to demonstrate that the ADS design is safe. And a simulation of an accident by a CFD code, could be a good source of demonstrating it.

The accident considered for this report is the following. After a certain working period of normal operation, there is a station blackout. So, the proton beam is switched off, there is a secondary coolant loss (it is assumed that once the secondary coolant is lost, it takes ten seconds, after the black out, to switch the beam off), and the bubble injection, used to help the primary coolant in its circulation, is also stopped. From that point, the coolant must circulate by natural convection, as the bubble injection has disappeared, and the reactor must remain coolable during the accident sequence.

The power law used for the decay heat power from the core has been taken from [2], and it is considered that the prototype has been working for almost two years.

$$P_d(t,T) = 0.0622 P_0 \left(t^{-0.2} - (T+t)^{-0.2} \right)$$

T = 6.0E+07, time at reactor full power.
t = cooling time.
P_0 = reactor power.
P_d = decay heat power.

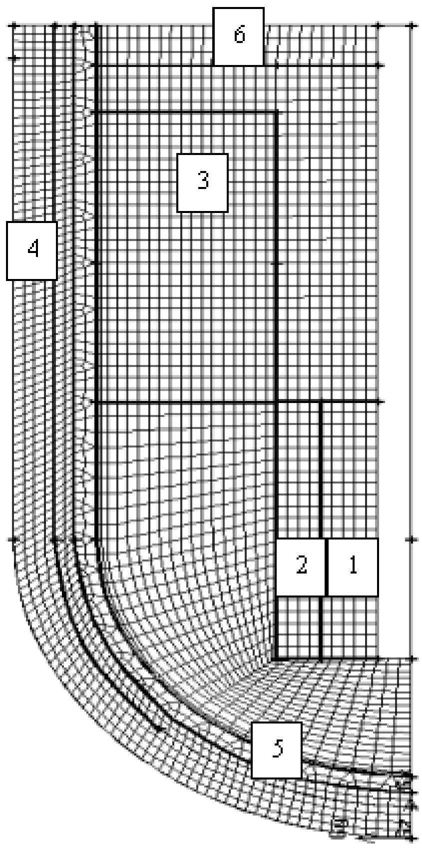
This transient will be running for 40 hours.

3. Fluent simulation inputs

Modelling of the ANSALDO's design includes the core, a riser cylinder and a heat exchanger (Number 3, in Figure 1) in the upper part of the downcomer, as well as a gas plenum on top of the fluid (Number 6). The vessel, the safety vessel around this one (the gap between the two vessels is depicted with Number 5), and the reactor vessel air coolant system (RVACS) (Number 4) are also modelled.

The simulation was done in a 2 D axysimmetric geometry, as shown in Figure 1. The total number of cells is 1 458, and they are all quadrilateral cells. This grid is the finest one of the two used in the paper, and the more similar to the STAR-CD one.

Figure 1. **Grid**



Some simplifications have been made in the geometry to get the best 2 D simulation. This can be seen in Figure 1.

For an axisymmetric geometry as this one, a cylindrical heat exchanger has been used, although this is not the real foreseen design. However, the dimensions have been adjusted to the ones of the ANSALDO's heat exchangers.

The core (Number 1) has 120 fuel assemblies, but to simplify the model, the tubes have been substituted by the pressure drop they produce. And the same has been done with the heat exchanger and the dummy assemblies (Number 2). These pressure drops are the ones indicated by [1], that is: 20 kPa inside the core, and 7 kPa for the heat exchangers. This last pressure drop has been calculated from the difference between the core and the total pressure drop, which is 29 kPa. 2kPa were assumed for the rest of the system.

Most of the fluid should pass through the core for cooling the fuel assemblies. So, a very small flow area has been assumed for the dummy assemblies, in order to get the Pb-Bi passing mainly through the core. The flow rates are: 5 345 kg/s through the core, and 491 kg/s through the dummy assemblies.

The proton beam is not represented, so, the power inserted in the core is a constant energy source. Then, the secondary circuit (the heat exchanger), is represented as a power sink. All the power generated in the core is taken out by the heat exchanger, so it is represented as a negative energy source.

The boundary conditions and the general data have been taken from [1].

There are several physical models involved in this simulation, so it is worth to mention them, and to give a brief explanation of the assumptions made. For more details see [4]:

- Basic models: continuity, momentum, energy.
- k-eps RNG model for the turbulence equations. This model was chosen because it is more accurate than the standard k-eps model, and it is not as elaborated as other models that solve the Navier-Stokes equations, taking into account the Reynolds stresses. A term that accounts for low-Reynolds numbers is included.
- The model used for radiation calculations is based on the expansion of the radiation intensity, I, into an orthogonal series of spherical harmonics, treating all walls as gray and diffuse.
- Density is treated as a constant, except in the buoyancy term in the momentum equation, that a Boussinesq approximation is used.
- Discrete phase model. This model has been included in order to simulate the injection of Argon to pump the primary coolant. The diameter of the bubbles is 1 mm, and they are injected 0.5 meters above the core outlet.

Another important point of the simulation is the material properties input. The Pb-Bi eutectic properties have been taken from [2] and [3].

Radiation is important in this simulation due to the high temperatures, and for the walls an emission of 0.7 has been input.

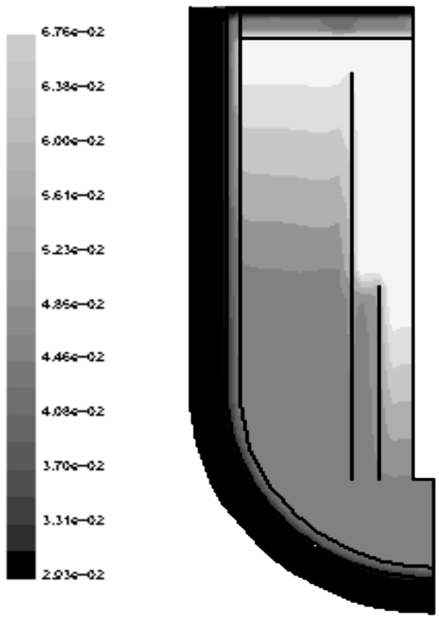
The partial differential equations describing the flow are transformed into discretized analytical equations. And for these calculations the first order UPWIND scheme is used for momentum and energy equations, and the second order UPWIND scheme for the turbulence equations.

4. Calculational results

4.1 The steady state

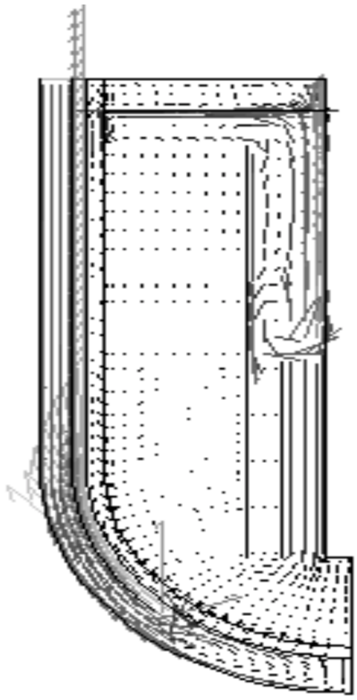
The whole problem, with all the above-mentioned models, is driven into a steady state. And to get to this situation, the injection of Argon and the use of the porous media model, to get the pressure drops in the display, are the main key. Figure 2 shows the evolution of temperature inside the vessels, as the flow is heated when going through the core, and getting colder in the heat exchanger. The maximum temperature is reached in the core outlet, 676 K. And once the coolant has gone through the heat-exchanger, the temperature goes down to 570 K, approximately.

Figure 2**. Contours of temperature**



There is some undesirable re-circulation above the dummy and below and above the heat exchanger (see Figure 3). Some of this re-circulation could be avoid with buffers above the core. And it is an option seriously taken for the final design.

Figure 3. **Velocity vectors**



Some of the lift force needed from the Argon is missed in the re-circulation, as some lines of bubbles are re-circulating in the main stream.

With this injection of bubbles, the correct velocities were reached, as well as the correct pressure drop and the proper temperature difference between the core inlet and the core outlet. Previous calculations without bubbles, could not reach the predicted velocities. And due to these lower velocities, temperatures were higher, up to 700 K (25 K increase).

In the next pictures (Figures 4 and 5), pressure drop, temperature difference and velocities are depicted. The average temperatures indicate that there is a difference of approximately 100 K between the core inlet and the core outlet. In the calculations, temperatures vary from 580 K at the core inlet, to 676 K at the core outlet, while in the ANSALDO's design 573.15 and 673.15 are foreseen.

Figure 4. **Temperature differences in the core**

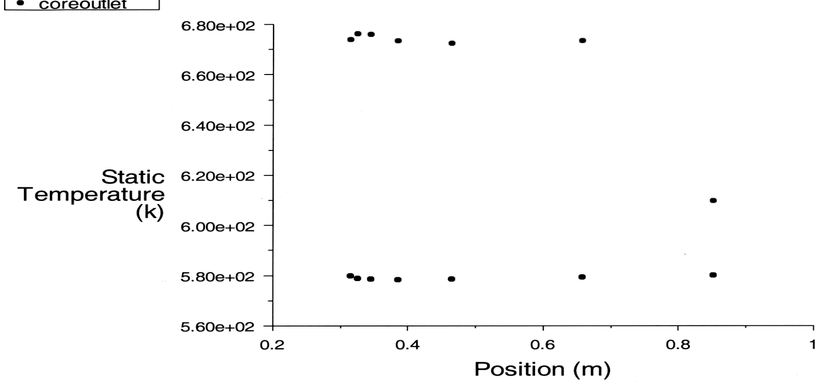
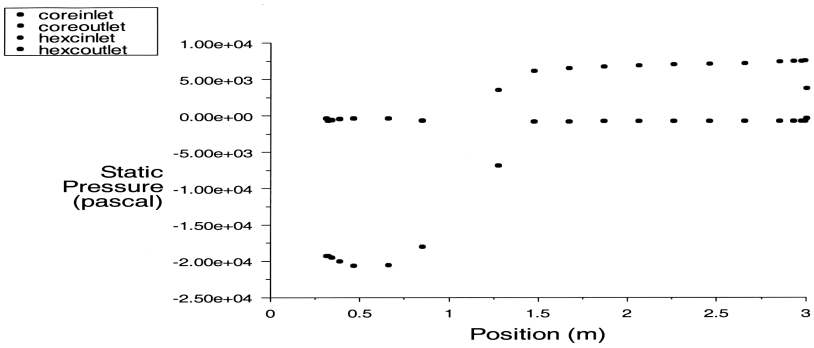


Figure 5. **Core and heat exchanger pressure drops**



The pressure drops were adjusted through the porous media model, as a momentum source inserted in the momentum equation.

In this Figure 5 it is shown that pressure drops of approximately 20 kPa in the core and 7 kPa in the heat exchangers are predicted by the calculations. And those are the pressure drops foreseen by ANSALDO. Once these pressure drops were the predicted ones, and the temperature was the correct one, the accident could be calculated.

4.2 The accident

The calculations have been done with the Argon injection switched off and a loss of the heat sink (the heat exchangers do not extract heat anymore), due to a station blackout accident.

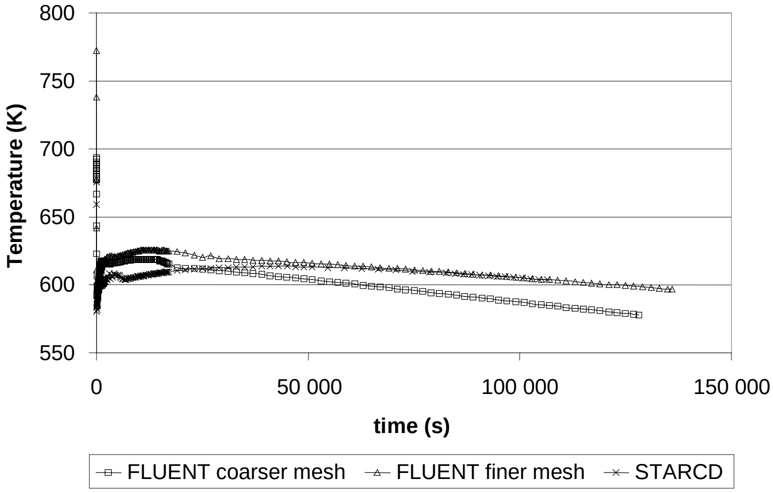
On the other hand, to make a conservative approach, it has been considered that there are ten seconds after the blackout, in which the proton beam is still working. So, the full power is on and the temperatures increase during this period by approximately 20 K (see Figure 6).

Once the beam power is off, the lead-bismuth coolant must be capable of managing the core cooling. At this point, the core is heated due to the decay heat power, and therefore, the energy source for the core heating is now determined by the function mentioned in the description of the simulation inputs.

The accident is assumed to continue for forty hours, and several conclusions can be drawn from these first results. The profile of the core outlet temperature is used to study the most important consequences of the accident considered.

The first calculation with FLUENT, with a very coarse mesh, shows that from the beginning of the blackout till the complete shut down of the proton beam (ten seconds), the temperature increases by 20 K, to 693 K. And once the power of the beam is off, and during the next 200 s, the temperature decreases 100 K, down to 590 K. Then, there is another escalation of temperatures at five hour after the accident.

Figure 6. **Temperature evolution at the core outlet**



The behaviour of the temperatures with a finer mesh, and the ones calculated by STAR-CD are qualitatively similar, but the actual values are somewhat different. FLUENT calculates a first peak of 772 K (100 K above the steady state temperature of 673 K), and STAR-CD predicts a temperature of 675 K from 659 K, in the steady state).

During this slope, a cloud of high temperature is formed above the heat exchanger that remains there for 7 000 seconds. The peak of 620 K is reached in the coarser mesh calculation by FLUENT; the STAR-CD calculation reaches 613 K, and the finer mesh calculation with FLUENT, 625 K. And from this time on the coolant begins to cool down, just by the natural convection of the Pb/Bi and the air. This means that the Pb-Bi boiling temperature is never reached (1 670 K). And what is more important, temperatures are always far below 1 273 K, a temperature above which vessel creep becomes a problem. At the end of these forty hours, the temperature has decreased to 573 K at the core outlet.

Another important result is the velocity decrease. From 0.42 m/s, the coolant circulation reduces to 8 mm/s in the period in which the mentioned temperature cloud is active (7 000 s). Then, it increases to 2.5 cm/s when the normal re-circulation is re-established.

The RVACS also assures the vessel cooling. This cooling is possible and useful because of the good conduction characteristics of lead-bismuth.

Recent FLUENT calculations have been made using an unsteady formulation to reach the steady state, instead of a direct steady state formulation. The core outlet temperature is 659 K, similar to the STAR-CD one. The maximum temperature peak in the STAR-CD calculations is twelve hours after the accident, while the FLUENT calculations that appear in this paper predict the peak five hours after the accident, and the new calculations, after eight hours of transient.

5. Conclusions

Results in this paper have been taken from the first running of a basic simulation of the ANSALDO's ADS design. No grid independence studies have been done, and the detailed comparison with the STAR-CD results is still to come. But some important conclusions can be extracted from this preliminary work:

- The good safety characteristics of lead-bismuth as a coolant for an ADS core. Its great heat capacity plus its high thermal conductivity are a good warranty for having time for an operator response, if necessary. A comparison between helium, water and lead-bismuth, shows the following properties at 700 K:
  - Pb-Bi: Thermal conductivity (k): 12.616 W/m.K; Specific heat (cp): 146.56 J/kg.K.
  - Helium: k: 0.152 W/m.K; cp: 5 193 J/kg.K.
  - Water: k: 0.6 W/m.K; cp: 4 182 J/kg.K.

  The passive way of functioning is an important safety item since fewer things can go wrong and human errors cannot play a role.

- One of the main problems to get the correct temperatures, has been the calculation of the porous media model parameters. The problem is that FLUENT considers all the area as totally open, so it is not possible to get the correct velocities in these geometries, because it considers velocities as if the cross section area is much larger than in reality. But once the correct momentum sources are calculated through the porous media model the core interior velocities should not lead to problems if the main flow is the correct one.

- The addition of bubbles has been the key to get the predicted velocities and temperatures. Since one is enhancing circulation, velocities are higher and temperatures are lower because of a better cooling. But it has also been interesting to do calculations without these bubbles, because it has been proven that natural circulation alone guarantees reactor cooling even without gas bubbles enhancing the flow. In this last case maximum temperatures get to 700 K, still far from the eutectic boiling temperature of 1 670°C.

- The vessel cooling by air is another important item of this ADS design. In this calculation the RVACS has been modelled as a cavity of air surrounding the safety vessel. But the original idea is to use several tubes, up to 84 U-tubes, with atmospheric air circulating through them.

  For this more complicated geometry a 3D simulation will be needed.

  The thermal condition of the external wall is isothermal, with a temperature of 293.15 K. This could lead to non-physical results, because it is not very realistic to have the same temperature during normal operation, and during the accident.

- Before some serious benchmark studies are done between FLUENT and STAR-CD calculations, some comparisons have been done, and results are similar except for one result. Temperatures are similar during the transient. For example, the maximum differences are only between 7 K to 10 K. This is not very much if we take into account that the simulations are not completely the same. In the steady state temperatures there are also differences (15 K approximately). But there is a very odd thing in the time when the maximum temperature is reached. While FLUENT predicts this maximum temperature at about five hours after the beginning of the accident, STAR-CD calculations predicts this time to be twelve hours. But as it has been mentioned, new FLUENT calculations using the unsteady formulation of the flux governing equations, seem to get more similar results compared with the STAR-CD ones. Tendencies, anyway, are similar, although FLUENT profiles show a quicker increase of temperature in the first seconds.

- Two main reasons can explain this large difference:
  - The injection of bubbles: while FLUENT models this injection of ARGON as a discrete phase interacting with the main flow, STAR-CD varies the density of the coolant above the core with a user defined function.
  - The convective heat transfer correlations: FLUENT is using default ones, and STAR-CD inputs some new ones taken from reference [2]:

On the air side: $Nu = 1.22\,\mathrm{Re}^{0.456}\,\mathrm{Pr}^{0.4}$
On the Pb-Bi side: $Nu = 0.5\,\mathrm{Re}^{0.5}\,\mathrm{Pr}^{0.5}$

- Calculations have been carried out with a first order discretization scheme, which gives more diffusive results. The stability of the solution is rather good, but not so the accuracy of the results.

  Calculations with a second order scheme must be done to assure better results.

- The grid used for the preliminary results is still very coarse, and a finer one is a necessity for grid independence results.

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