BENCHMARKING ACTIVITY ON ENEA AVAILABLE TOOLS FOR THE DYNAMIC ANALYSIS OF LBE COOLED SUB-CRITICAL SYSTEMS

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Abstract

Following the large interest aroused in the world on accelerator-driven systems (ADS), the TRASCO Italian national research programme for nuclear waste transmutation has paid special attention to the development of suitable numerical tools for studying operational transients and accidental sequences of ADS-like systems.

At present a multi-group dedicated neutronic code for sub-critical systems coupled with a simplified thermal-hydraulic code (NILO-TIESTE) and a modified version of the RELAP5/PARCS code are both available.

The aim of this work is to test and compare these two coupled codes against a set of typical transients for lead-bismuth cooled sub-critical systems under cover gas injection enhanced natural circulation.

Introduction

The accelerator-driven systems (ADS), which couple a high energy high current proton accelerator with a sub-critical reactor, have a great potential as transmuting systems both for transuranic elements (TRUs) and long-lived nuclear wastes (LLWs) with a high degree of inherent safety, thus looking as an interesting solution for the closure of the nuclear cycle. [1]

Following the large interest aroused in the whole world on such systems, since 1996 several basic R&D Italian activities were concentrated in a national research programme funded by MURST (Italian Ministry of the University, Scientific and Technological Research). Within the framework of this programme (TRASCO, the acronym for "Trasmutazione Scorie", namely "Transmutation of Wastes") the feasibility and operability of a Pb-Bi cooled ADS prototype is currently under investigation.

Development and validation of suitable tools for studying the dynamical behaviour of such a system, taking into account interdependence between neutronics and thermal-hydraulics, are clearly a crucial issue among the R&D needs.

Two parallel strategies have been pursued by ENEA within the frame of TRASCO research programme. The first relies on the development of a multi-group dedicated neutronic code for sub-critical systems (NILO) that takes into account the thermal feedback by means of a simplified thermal-hydraulic model of the reactor channel (TIESTE). [2] The second aims at modifying the pre-existing coupled code RELAP5/PARCS, [3] originally developed for water cooled critical systems. The neutronic module PARCS solves the tri-dimensional two-group time-dependent diffusion equation for neutrons while the thermal-hydraulic module RELAP5 provides the thermal-hydraulic analysis of the system. [4] These tools, now both available, present complementary capability: NILO-TIESTE enables a detailed description of the neutronic population evolution for core design, whereas RELAP5/PARCS is devoted to the analysis of operational transients and accidental sequences thanks to the RELAP5 capability to simulate the whole thermal-hydraulic system.

In order to understand the effect of the different detail for the neutronic and thermo-hydraulic models, this paper deals with the comparison of the two codes by means of a set of transient calculations for a simplified loop representing a lead-bismuth cooled sub-critical system with natural circulation enhanced by incondensable gas injection. These calculations concern some transients considered exemplifying of the dynamic behaviour for this kind of system, namely, an instantaneous switching off of the external source with re-insertion and a secondary system overcooling.

Tools description

In order to achieve a suitable code for system analysis of a Pb-Bi cooled ADS, the authors of the present work from ENEA Bologna research centre, within the framework of a TRASCO co-operation with ANSALDO and University of PISA, decided to modify the existing coupled code RELAP5/PARCS by introducing a consistent set of physical and thermodynamic properties for Pb and Pb-Bi alloys in the modules devoted to evaluating heat and mass transport and by introducing the external neutron source into the neutronic modules. [5]

Several original RELAP5 routines have been updated in order to implement suitable correlation, based on the soft sphere model for liquid metals, to generate the reference physical and thermodynamic properties for Pb and Pb-Bi, namely thermal conductivity, surface tension and fluid viscosity. Similarly, some specific heat transfer correlation for liquid metals have been added, based on the so-called Subbotin correlation. All these modifications, letting the modified coupled code RELAP5/PARCS deal with Pb and Pb-Bi as two-phase fluids also in presence of non-condensable gas, give the possibility to simulate fully natural circulation or cover gas injection enhanced natural circulation of Pb-Bi, as proposed for the XADS prototype. [6]

Neutronic code PARCS, originally developed under NRC contract by Purdue University School of Nuclear Engineering for water cooled critical reactors, [7] solves the time-dependent two-group neutron diffusion equation in tridimensional Cartesian geometry by using a hybrid scheme based on analytical nodal method (ANM) and nodal expansion method (NEM). The code can provide k_{eff} calculation and simulation of a large number of transients, originated both by control rod movements and by a large number of thermal-hydraulic or neutronic events. The possibility of using the coupled code RELAP5/PARCS for the analysis of fast spectrum sub-critical systems has required, first of all, the external neutron source terms to be introduced in neutron diffusion equations and, secondly, an extensive modification of the same neutron diffusion equations in order to deal with fast spectra. All these PARCS modifications let the modified coupled code RELAP5/PARCS deal with fast spectrum sub-critical systems. [6]

The authors of the present work from ENEA Casaccia research centre, in collaboration with the Reactor Physics group of the Polytechnic of Turin, decided to develop a multi-group dedicated neutronic code for sub-critical systems (NILO), eventually coupled with a multi-channel thermal-hydraulic code (TIESTE). [8]

The multi-channel code TIESTE provides the thermal-hydraulic analysis of a reactor core. It can work coupled with a 0-dimension reactor kinetics or with the time-dependent multi-group r-z neutronic description, specifically developed in NILO in order to enable a detailed description of the neutronic population evolution for sub-critical core design and safety analysis.

Either RELAP5/PARCS or NILO-TIESTE are conceived to take into account thermal feedback on neutron power level due, for instance, to moderator density variation and doppler effect. Nevertheless, owing to the modest extent of these contributions in liquid metal cooled fast spectrum systems, they result negligible in the transients studied in the present paper.

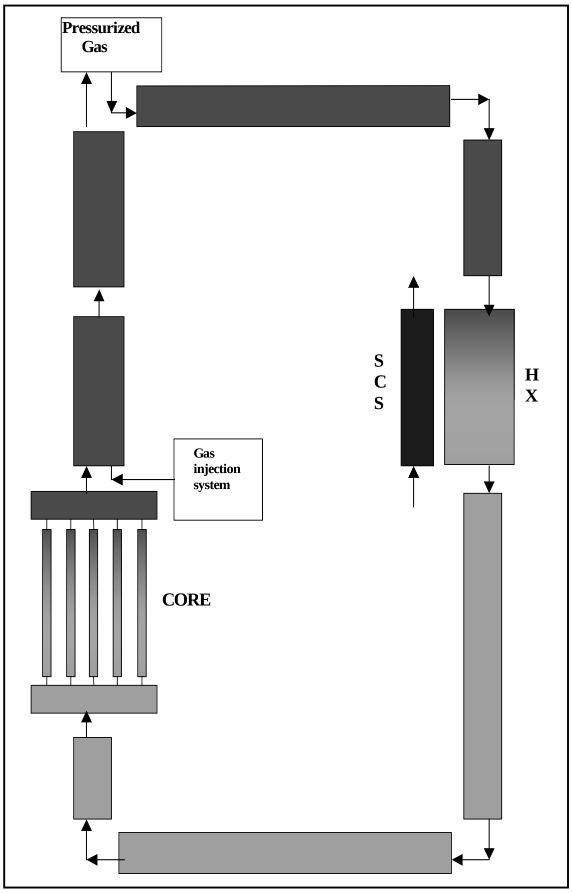
Simplified simulation of a Pb-Bi cooled sub-critical system

In order to test and compare the modified version of RELAP5/PARCS and NILO-TIESTE, a simplified Pb-Bi cooled fast spectrum sub-critical system has been considered. This system intends to be a rough representation of the Italian accelerator-driven prototype XADS and its simulation aims at highlighting the effect of the different detail for the neutronic and thermal-hydraulic models which characterise the two coupled codes.

A very elementary scheme of the system, corresponding to the RELAP5 nodalisation, is shown in Figure 1. It reproduces a Pb-Bi loop characterised by a total length of 16.55 m and an elevation of 6.275 m. The sub-critical core region (reference k_{eff} = 0.9769 and total neutron source output of about 1.8 10^{17} n/s) is simulated by 6 channels, 0.87 m high, (5 fueled with SPX-like MOX fuel elements (β = 0.00357) generating a total nominal power of 80 MW). The circulation of liquid Pb-Bi relies only on natural convection enhanced by incondensable gas injection and a nominal Pb-Bi mass flow rate of about 5 500 kg/s, as in the XADS reference system, [9] can be obtained by a suitable adjustment of pressure drops along the loop.

Self-explaining schemes of the core radial and axial structure are shown in Figure 2. Active elements (coloured red, orange and yellow) can be gathered in 5 rings, preserving the total Pb-Bi flow areas. By the same way, for instance, single element areas have to be respected when passing from the original fuel element hexagonal geometry to the Cartesian one requested for the PARCS input. All the nuclear data, for instance in the case of RELAP5/PARCS in the two-group format and with an energy-optimised cross-section calculation characterised by a 0.82 MeV separation energy, have been provided by Casaccia ENEA Research Centre. [10]

Figure 1. **A very elementary scheme of the considered Pb-Bi cooled sub-critical system, corresponding to the RELAP5 nodalisation**

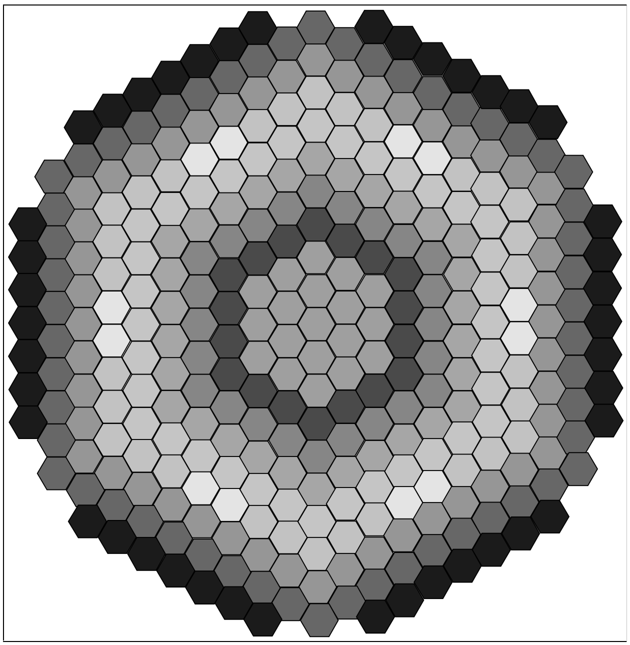


Description of the analysed transients

Two different kinds of transients, that emphasise the behaviour of sub-critical systems under natural circulation enhanced by incondensable gas injection, have been analysed using the NILO-TIESTE and the modified RELAP5/PARCS coupled codes.

In the first type of transient, the recursive switching off and reinsertion of the neutron external source permit to test and compare the two coupled codes concerning the possibility of adequately describe the dynamical behaviour of the system in case of abrupt power perturbations. Starting from a fully stationary system, the neutron external source is completely switched off in about 1 ms. Then the neutron external source is reinserted after 6 s by switching on the accelerator, supposed to reach its previous nominal power in 1 ms. The evolution of the system that depends on the proper description of the neutronic population evolution is studied for 40 s.

Figure 2. **Self-explaining schemes of the radial and axial structure of the sub-critical core**

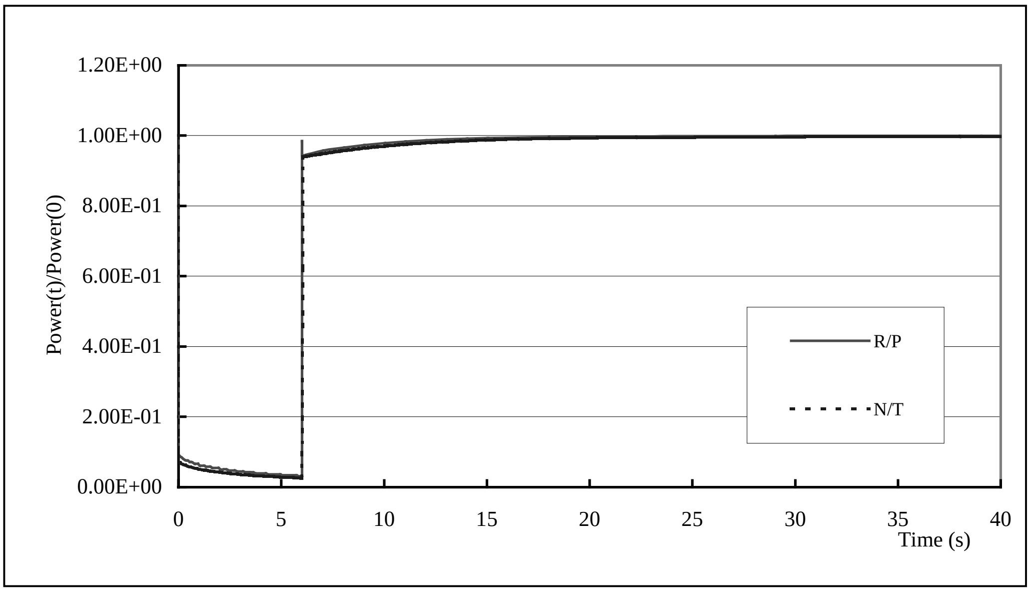


The second type of transient concerns a secondary system fluid overcooling. Starting from the nominal stationary conditions, the temperature of the secondary cooling circuit is reduced in such a way that the Pb-Bi temperature at core inlet undergoes a 30 degree reduction in about 5 s. The neutron external source, driven by the proton accelerator, is supposed to remain constant. Although a such kind of transient gives the possibility to check the overall response of the codes, especially in case of coupling between neutronics and thermal-hydraulics, the thermal feedback on neutronic power has not been taken into account in the compared calculations. This choice is due to the reduced temperature excursions that make negligible its effect respect to the different detail in the thermal-hydraulic description. Anyway, an evaluation of this effect is given by means of RELAP5/PARCS re-calculations of both transients.

Comparison and discussion of the results

For the first type of transient the total sub-critical reactor power evolution, calculated by the two codes (NILO-TIESTE, in the following N/T and RELAP5/PARCS, in the following R/P), is presented as a function of time.

Figure 3. **Ratio of the sub-critical reactor power P(t) to P(t = 0) as a function of time**



The evolution of the ratio of the sub-critical reactor power **P(t)** to **P(t = 0)** predicted by the two codes is very similar: the value just after accelerator switching off is 7.4% for N/T and 8.9% for R/P while just after accelerator reinsertion is 93% for N/T and 94.3% for R/P. After 40 s of transient the power has almost reaches its nominal value in both calculations (9.99% for R/P and 9.98% for N/T). A general agreement between the temperatures of the primary coolant at core inlet and outlet can also be observed looking at Figure 4. The minimum value at core outlet (nominal value 673.15 K) results 615.5 K for N/T and 602.3 K for R/P. Moreover, the effect of a different detail in the thermal-hydraulic description of the loop is evident on the core inlet temperature that in N/T calculation shows a more evident decrease than in R/P calculation.

Figure 4. **Pb-Bi temperatures at core inlet (T in) and outlet (T out)**

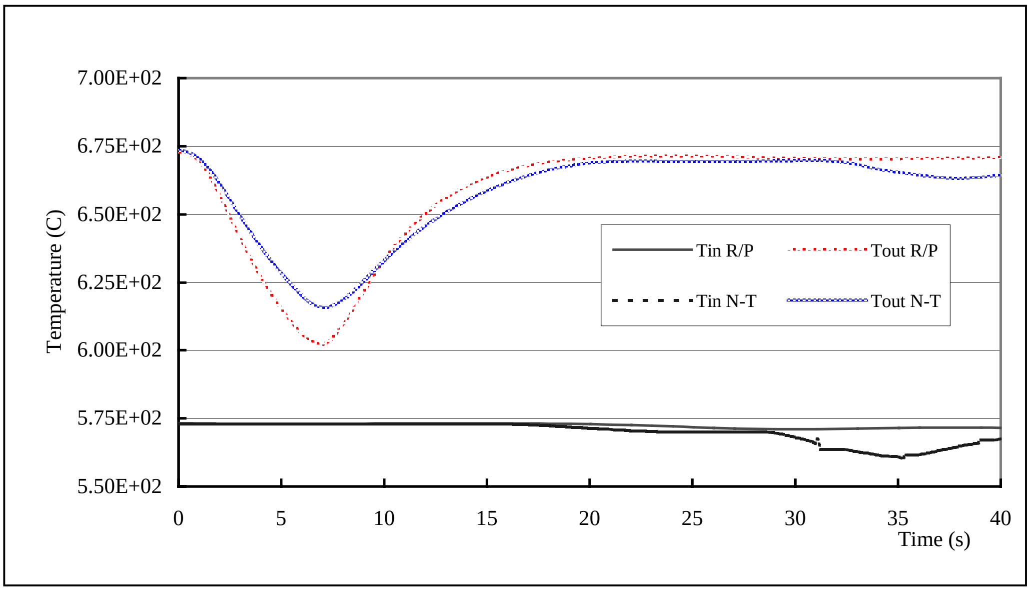
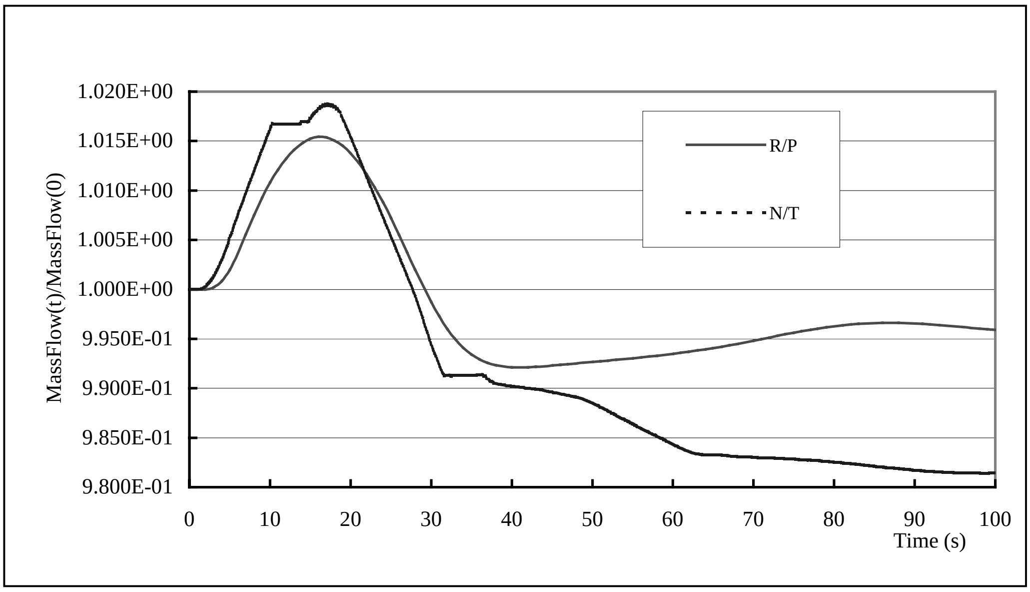
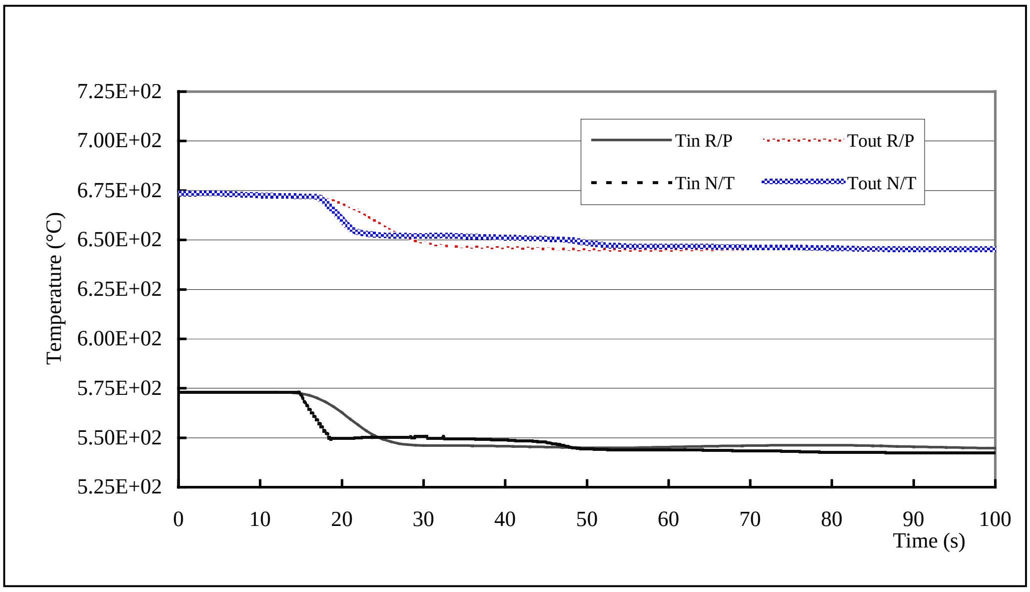


Figure 5. **Ratio of the Pb-Bi mass flowrate through the core M (t) to M (t = 0)**



For the second type of transient the ratio of the Pb-Bi mass flowrate through the core **M (t)** to **M (t = 0)** as a function of time, calculated by N/T and by R/P, is presented in Figure 5. In Figure 6 are presented the temperatures of the primary coolant at core inlet (**T in**) and outlet (**T out**) as functions of time, calculated by N/T and by R/P. As already stated, thermal feedback on neutronics has not been taken into account.

Figure 6. **Pb-Bi temperatures at core inlet (T in) and outlet (T out)**



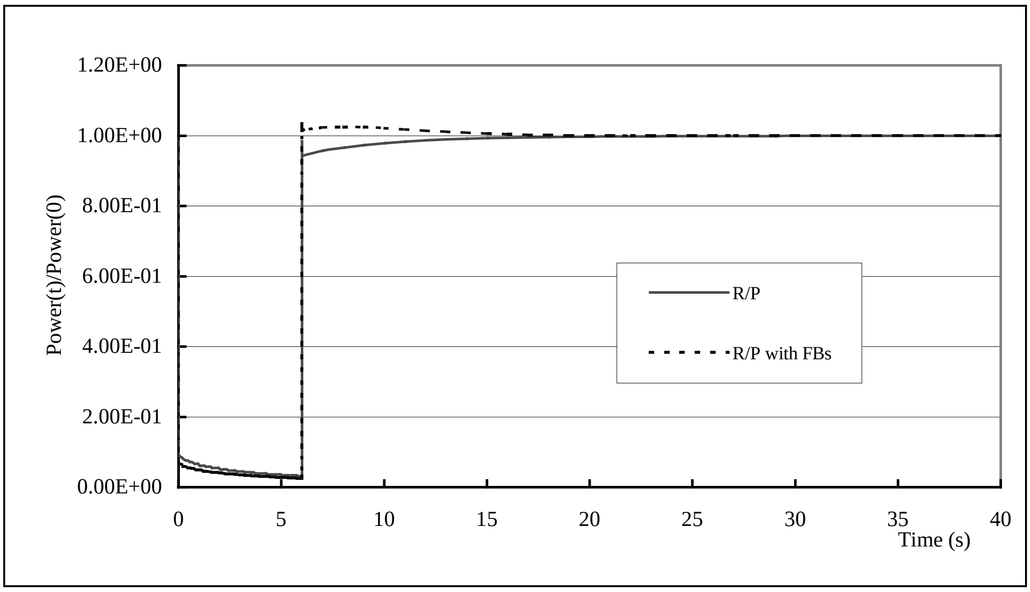
Also for this transient the global agreement between the two codes is surely acceptable. In particular, in the first part of the transient, the increase of mass flowrate due to the overcooling results similar: 101.8% for N/T and 101.5% for R/P. The simplified thermal-hydraulic model of N/T is not able to take into account the. The differences between the temperature profiles at core inlet and outlet are due to the different thermal-hydraulic models which characterise the two codes.

In the following, in order to estimate the effect of thermal feedback on the dynamic behaviour of the XADS prototype, the results of the previous two transients, calculated by R/P taking into account the thermal feedback on neutronic power level, are presented and briefly discussed.

For the first type of transient the total sub-critical reactor power evolution calculated with and without taking into account the thermal feedback is compared in Figure 7 and the Pb-Bi temperatures at core inlet and outlet are compared in Figure 8.

Thermal feedback is responsible of the slight differences in the reactor neutronic power behaviour: the value of the ratio of **P(t)** to **P(t = 0)** just after accelerator switching off is 6.73% against 8.92%, while a couple of seconds after accelerator reinsertion a maximum value of 102.4% (against 94.6%) is reached and an over power is present until 20 sec when the initial temperatures are re-established. Concerning the Pb-Bi temperatures at core inlet and outlet no noticeable difference can be noted.

Figure 7. **Ratio of the sub-critical reactor power P(t) to P(t = 0) calculated by R/P**



For the second type of transient the total sub-critical reactor power evolution as a function of time is presented in Figure 11. In Figure 13 the ratio of the Pb-Bi mass flowrate through the core **M(t)** to **M(t = 0)** as a function of time is presented.

Taking into account thermal feedback one could expect a different oscillating response of the system. This behaviour is slightly evident in the ratio of the Pb-Bi mass flowrate through the core (see Figure 9), as the thermal feedback has a limited effect on neutronic power that increases less then 2% (see Figure 10).

Figure 8. **Pb-Bi temperatures at core inlet (T in) and outlet (T out) calculated by R/P**

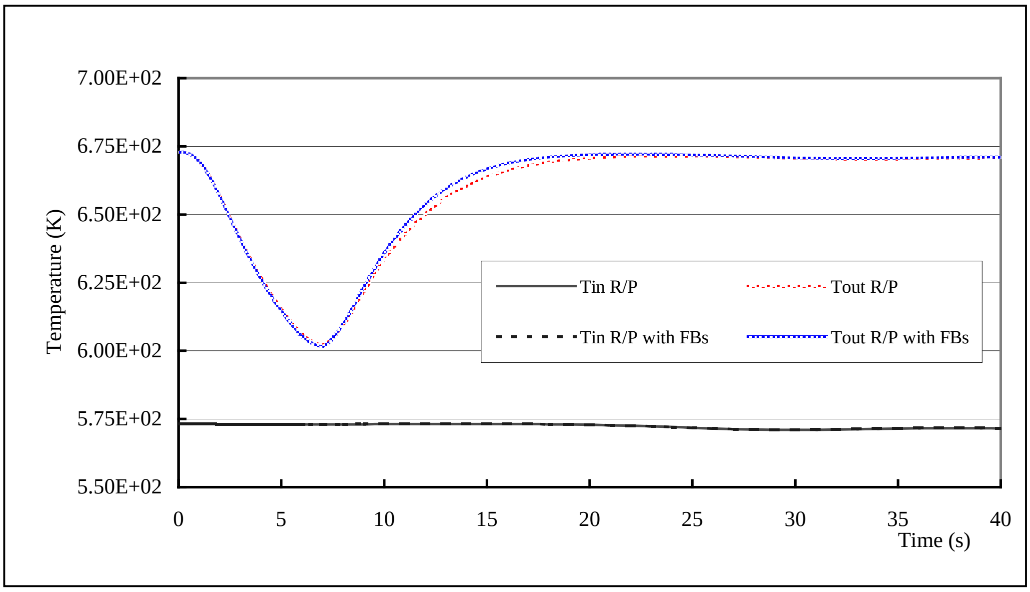
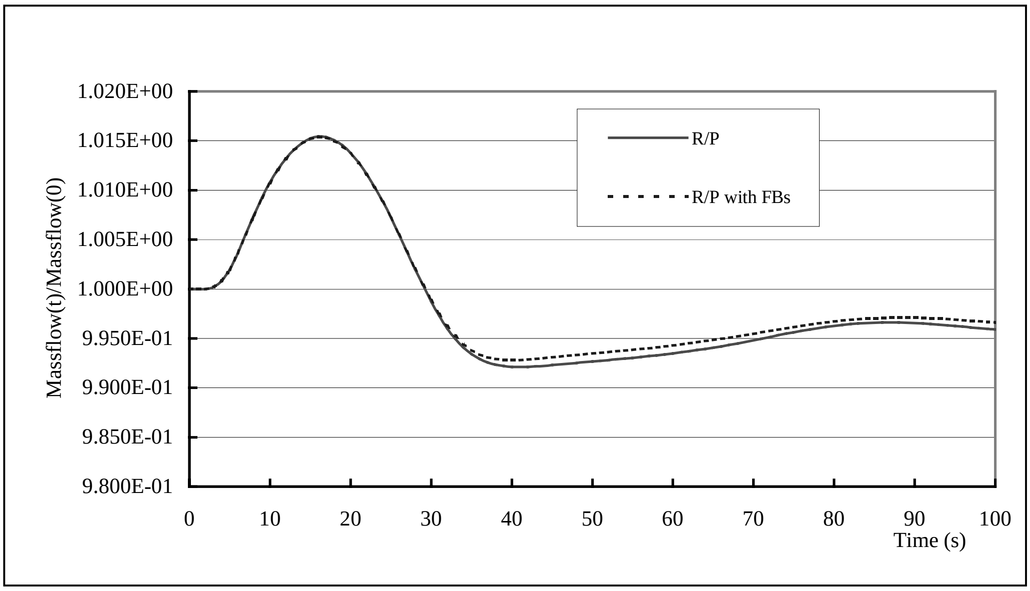


Figure 9. **Ratio of the sub-critical reactor power P(t) to P(t = 0) calculated by R/P**



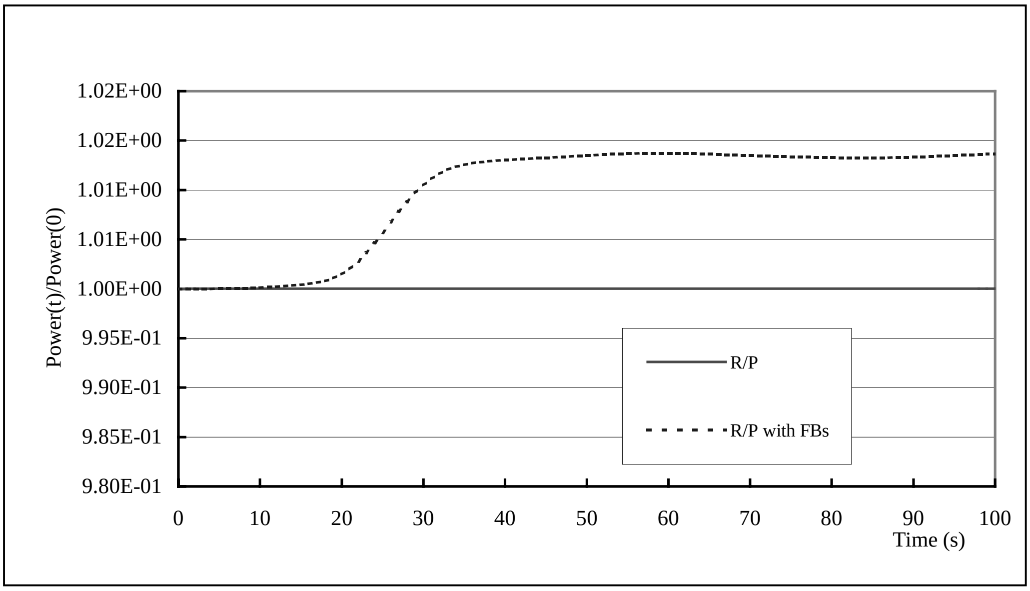
Conclusions

This paper has dealt with the comparison of the coupled codes NILO-TIESTE and RELAP5/PARCS, now both available in ENEA for the analysis of the dynamical behaviour of lead-bismuth cooled ADS.

The comparison, worked out by means of a set of transient calculations for a simplified loop representing a lead-bismuth cooled sub-critical system with natural circulation enhanced by incondensable gas injection, has shown a general equivalence in terms of transient calculation even if the two coupled codes present different capabilities and aims: NILO-TIESTE enables a detailed description of the neutronic population evolution for core design while RELAP5/PARCS permits to work out the analysis of operational transients and accidental sequences of the whole system.

The comparison has also shown and confirmed, as expected, that thermal feedback has a limited effect on the global behaviour of lead-bismuth cooled ADS like the XADS prototype.

Figure 10. **Pb-Bi temperatures at core inlet (T in) and outlet (T out) calculated by R/P**



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