Set Up and Preliminary Assessment of a 3D Numerical Model for the Thermo-Fluid Dynamics Analysis of an Open Square Lattice Core of a Lead Cooled Reactor

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SET UP AND PRELIMINARY ASSESSMENT OF A 3D NUMERICAL MODEL FOR THE THERMO-FLUID DYNAMICS ANALYSIS OF AN OPEN SQUARE LATTICE CORE OF A LEAD COOLED REACTOR

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Sommario
This report describes the set up of a simplified three-dimension numerical model for the thermo-fluid dynamic analysis of an open square lattice reactor core lead cooled on the basis of a three-dimension CFD computer code developed by DIENCA UniBo. A preliminary assessment of the model has been performed by comparing its results with the T/H reactor core behavior predicted with a one-dimension independent channel model based on RELAP5 code. To this purpose the conceptual design of the LFR core developed in the framework of the ELSY EU collaborative project has been adopted as a reference. Moreover, in order to support the set-up of the model, some results of the CFD analysis for fuel bundle of liquid metal reactors have been considered.
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1. Introduction

Within the framework of national AdP ENEA-MSE and international R&D programs ELSY collaborative project [1] several innovative solutions for a liquid metal fast reactor design are being investigated. Among these solutions the open-assembly core option adopted by ENEA for the preliminary neutronic analysis of the ELSY reactors requires a new approach to the thermal-hydraulic core design respect to the previous already well-established design of Liquid Metal Reactor [2]. Therefore ENEA have planned to follow a two-step approach at the T/H analysis of the core:

- utilization of a one-dimensional RELAP5 model for independent channels analysis for a prompt verification of the thermal-hydraulic and safety of the core neutronic design.
- development of a dedicated tool for the evaluation of the intermingled effects between assembly flows.

While the preliminary evaluation with RELAP are already in progress within the frame of the European Project, the development of a full 3D CFD code with the purpose of analyzing the whole core behavior has been undertaken within the frame of the AdP ENEA-MSE. To this purpose the DIENCA department of the University of Bologna has determined and implemented a suitable resolution scheme of full three-dimensional incompressible Navier-Stokes and energy equations. The numerical simulations take place at a coarse, assembly length level and are linked to the fine, sub-channel level state through transfer operators based on parametric coefficients that summarize local fluctuations. The overall effects between assembly flows are evaluated by using average assembly turbulent viscosity and energy exchange coefficients. For an exhaustive description of the physical-mathematical CFD program employed, see reference [3].

ENEA has performed a preliminary assessment comparing the 3D results obtained for a characteristic lead cooled open core with the results obtained with the RELAP5 one-dimensional independent channels approach. Moreover, a first estimation of the average assembly turbulent viscosity and energy exchange coefficients have been carried out on the basis of pre-existing CFD simulations over limited subassembly regions. Finally, the pressure distribution in the upper and lower plenum has been considered as boundary conditions for the 3D model of the open core, in order to obtain a first evaluation of the effect of the flow patterns in the plena on the intermingled effects between assembly flows.
2. Set-up of the 3D model for a Lead Cooled Reactor Core

Reminding to the reference [3] for detailed information about the numerical algorithm, it is recalled here the main characteristic of the full 3D code. The purpose of this code is to investigate three-dimensional pressure, velocity and temperature fields inside nuclear reactors at the coarse fuel assembly level when all the sub-channel details are summarized in parametric coefficients.

The model of the ELSY core have been set up in order to be benchmarked with a RELAP5 model with separated channels. To this purpose some simplifying assumptions have been introduced:

- any core assembly is considered an homogeneous and continuous lattice of fuel pins;
- the radial exchange of momentum and energy is modeled with empirical coefficients [4];
- turbulence effects are modeled with a simple LES approach;
- pressure losses are modeled by using standard mono-dimensional correlations;
- the dummy/reflecter region and control rod assemblies are not simulated.

The three-dimensional code solves the Navier-Stokes equations coupled with the incompressibility constraint and the energy equation in the reactor domain where lamped coefficients are use to model the sub-grid structures and forces. The values of these coefficients are still an open question and standard generic correlations are used in this computation for momentum and energy exchange coefficients [5-6].

2.1 ELSY Core Geometry

In the framework of the studies for the next generation of nuclear power plant well-known as GEN-IV [7], the ELSY (European Lead cooled System) project of the VI European Framework Program is addressed at the development of an European LFR (Lead Fast Reactor) design. It aims at investigating the technical/economical feasibility of a high power critical fast reactor with waste transmutation capability responding to the requirements of sustainability, non-proliferation and energy production at lower costs.

Such an innovative project needs the investigation of different design solutions that concern the overall power plant. The present study focuses the attention on the open square fuel assembly (FA) option. The advantages to consider FAs without wrapper are quite evident e.g. the in-vessel structures weight are reduced, there are lesser absorber materials in the active core region, an increased power density, lesser risks of FA blockage, the reduction of the hot-spot temperatures, etc.

The ELSY reactor core consists of an array of 162 FAs wrapperless [8] with three different fuel enrichment in plutonium and 80 surrounding dummy/reflecter assemblies. The reactor is controlled by 8 scram control rods plus 70 finger absorbers sparse in the core for scram and regulation. In Fig. 1, it is shown a schematic view of ELSY core.
The structure of the fuel assembly is characterized by a square lattice of 21 by 21 fuel pins of which the four angular ones are replaced with stainless steel structure for mechanical reason. It is peculiar the presence of a structural void square tube located in the assembly centerline to host the finger absorber replacing 3 by 3 pins. The fuel pins are supported along their lengths with five spacer grids to maintain the distances among them. The fuel adopted is a MOX with three different plutonium enrichment (radially increase) and the clad is the ferritic-martensitic stainless steel T91. In particular, the fuel is hollowed to increase the volume for the gaseous fission products, solution that allow to reach a burnup up to 100 MWd/kg of heavy metal. Fig. 2 shows the fuel assembly and fuel pin design and dimensions.

Fig. 1 – Scheme of ELSY core.

Fig. 2 – Design and dimensions [mm] of fuel assembly and fuel pin.
The model meshing and its x, y, z view are shown in Fig. 3. Each assembly is represented by 4×4×20 Hex27 finite elements. For the quarter reactor the number of nodes are 116481, the dofs 481485 (velocity, pressure and temperature) and the elements are 15561. In this case the domain is discretized by standard Lagrangian finite element families which satisfy the standard approximation properties. In order to solve the pressure, velocity and energy field it is used the finite space of linear polynomials for pressure and the finite space of quadratic polynomials for velocity and energy.

![Fig. 3 – Full reactor and computational domain](image)

The fuel assembly dimension is extended up to 29.4cm due to thermal expansion at working condition temperature 400°C. Axially the computational description considers a region which is 0.9m below and 0.2m above the core for a total of 2m. The heat generation zone or the active core zone for the reactor starts at H_{in} = 0.9m and ends at H_{out} = 1.8m. Due to the fact that the model describes the reactor at assembly level, the sub-assembly composition is seen as an homogeneous medium. Data about this composition can be found in Tab. 1.

<table>
<thead>
<tr>
<th>area (m^2)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pin area</td>
<td>370.606 × 10^{-4}</td>
</tr>
<tr>
<td>Corner box area</td>
<td>5.717 × 10^{-4}</td>
</tr>
<tr>
<td>Central box beam</td>
<td>2.092 × 10^{-4}</td>
</tr>
<tr>
<td>Channel central box beam area</td>
<td>12.340 × 10^{-4}</td>
</tr>
<tr>
<td>Coolant area</td>
<td>473.605 × 10^{-4}</td>
</tr>
<tr>
<td>Assembly area</td>
<td>864.360 × 10^{-4}</td>
</tr>
<tr>
<td>Coolant/Assembly ratio</td>
<td>0.548</td>
</tr>
</tbody>
</table>

Tab. 1– Coolant Assembly Area Ratio Data
2.2 Core Power Distribution

The power generated by ELSY reactor is 1500MWth. At the beginning of cycle (BOC) conditions considered for the present work, the power can be split among the fuel regions inner, intermediate and outer respectively in about 501, 489 and 492MWth. Part of the total power, about 18MWth, is deposited in the dummy/reflector region and in structural materials above and below the active core region. This power is not taken into account in the models.

In Fig. 4 it is shown the scheme and labeling of the quarter reactor computed, scheme that will be used to compare the results between CFD and RELAP5. The relative table shows the power produced in each fuel assembly.

![Scheme and labeling of reactor modeled and power generated in each FA](image)

(* power referred to the entire fuel assembly)

The subsequent Tab. 2 summarizes the power produced by ELSY and put in evidence the average power and the correspondent radial form factor referred to each fuel zone which is defined as the ratio of maximum power and average power.

<table>
<thead>
<tr>
<th></th>
<th>Power [MWth]</th>
<th>P_avg [MWth]</th>
<th>ffrad</th>
</tr>
</thead>
<tbody>
<tr>
<td>INNER</td>
<td>501.41</td>
<td>56</td>
<td>8.95</td>
</tr>
<tr>
<td>INTERMEDIATE</td>
<td>489.23</td>
<td>50</td>
<td>9.78</td>
</tr>
<tr>
<td>OUTER</td>
<td>491.60</td>
<td>56</td>
<td>8.78</td>
</tr>
<tr>
<td>TOTAL</td>
<td>1482.24</td>
<td>162</td>
<td>9.15</td>
</tr>
</tbody>
</table>

Tab. 2 – Power of ELSY Reactor and Radial Form Factor
The axial power distributions adopted for the different fuel zones are shown in Fig. 5 with the correspondent axial form factor.

![Fig. 5 – Axial Power Distributions and Form Factor](image)

For the given power of 1482.2MWth and the lead heat-up over the core of 80°C (mixing temperature), the lead mass flowrate is fixed to a value of 124540 kg/s.

### 2.3 Pressure Drops Distribution

The distributed friction losses are calculated with the Coolebrook-White correlation imposing a walls roughness of 3.0e-6m. The concentrated pressure drops, limiting the attention at the core region, are due to the abrupt area change at core inlet, to the presence of five spacer grids with a relative plugging of 0.33 and finally to the area change at core outlet.

The grid spacers pressure drop are evaluated using Rehme approach [10], considering a lead velocity of 1.6m/s (obtained fixing the flow area and the mass flowrate) and the relative plugging. The relative pressure drop calculated results of about 7000Pa each grid that correspond to a factor k=0.52. Contraction and expansion pressure drops at core inlet and outlet are taken into account by means of concentrated coefficients k=0.5 at core inlet and k=1.0 at outlet. The Tab. 3 summarizes the concentrated pressure drops assumed.

<table>
<thead>
<tr>
<th>k factor</th>
</tr>
</thead>
</table>
| Core Inlet | 0.50  
| Spacer Grid (5) | 0.52  
| Core Outlet | 1.00  

Tab. 3 – Concentrated Pressure Drops
There is another concentrated pressure drop that could have an important effect on the core thermal-hydraulics due to the presence of cylindrical support structures of finger absorbers. Their presence causes an additional pressure drop along the path from the FA nozzle outlet to the pumps inlet that decrease radially, see Fig. 6.

![Sketch of the lead flow motion in ELSY](image)

**Fig. 6 – Sketch of the lead flow motion in ELSY**

This pressure drop have a fall back in the fluid dynamic behavior of the whole core, this is true in particular for the open square fuel assembly because it creates a radial pressure distribution at the core outlet with effects on the flow patterns among the assemblies. It is expected an increase of the radial flow component through the assemblies with a more uniform outlet mixing temperature. The relative pressure distribution at the core outlet, evaluated with correlation in literature [11], has been assumed as a boundary condition to take into account this effect. Fig. 7 shows the radial distribution of this additional pressure drop.

![Outlet Pressure Drop Distribution](image)

**Fig. 7 – Outlet Pressure Drop Distribution**
3. Assessment of the 3D model against a one-dimension independent channel analysis

In a first phase the thermal-hydraulic code RELAP5, modified to treat heavy liquid metal [12], has been used to have a conservative evaluation on the system/core behavior at nominal and accidental conditions and for safety purpose. Although the limits of RELAP5 bring to have an approach remarkably conservative in the simulation of the open core thermo-fluid dynamics, in this work it is adopted to assess the dedicated full 3D CFD code previously described that allows taking into account the intermingled effects among assembly flows.

3.1 RELAP5 Core Model

The results of the core simulation obtained with the model described in the previous chapter will be compared against the results obtained with a model developed for RELAP5 code [13] to verify and appreciate the effects of the “open” square lattice reactor e.g. cross flow and thermal exchange through the assemblies.

The model developed for RELAP5 code is based on the idea to simulate each FA with an independent channel, taking advantage of core symmetry the description is limited to a quarter reactor as shown in Fig. 4. The dummy reflector and control rod assemblies are not taken into account, this means that the separate channel model of the reactor consist of 46 parallel channel (18 FA inner, 13 FA intermediate and 15 FA outer) each one connected with an upper and lower junction to the volumes that represent the plenum as shown in Fig. 8.

Fig. 8 – Scheme of RELAP5 independent channels model
The half sub-assemblies placed on the edge of modeled region are simulated with half flow area and relative half power. The boundary conditions imposed are:

- core inlet temperature of 400°C in the lower plenum
- core mass flowrate at the inlet time-dependent junction of 124540 kg/s to have a mixing outlet temperature of 480°C at a given thermal power produced (1482.2MWth)

Each pipe/FA of Fig. 8 is divided in 16 axial meshes and a fuel pin thermal structure is associated at the active core height starting from 0.9m up to 1.8m along 10 axial meshes useful to define the axial power distribution.

The distributed pressure drops are computed directly by the code the Zigrang-Sylvester engineering approximation to the Coolebrook-White correlation and the concentrated pressure drops at inlet, outlet and five spacers grids are introduced as a k factor as described in §2.3.

The heat transfer correlation implemented is the Zhukov correlation without spacers as suggested for square lattice pins by the ELSY technical group [14].

$$N_u = 7.55x - 11x^{-2} + 0.007Pe^{0.54+0.85x}$$

The main thermal-hydraulic parameters used to assess the model and referred to the whole reactor core are reported in the Tab. 4.

<table>
<thead>
<tr>
<th>GEOMETRY</th>
<th>FA Grid</th>
<th>21x21</th>
</tr>
</thead>
<tbody>
<tr>
<td># FA</td>
<td>162</td>
<td></td>
</tr>
<tr>
<td>pin/FA</td>
<td>428</td>
<td></td>
</tr>
<tr>
<td>FA Side (expanded)</td>
<td>0.2940 m</td>
<td></td>
</tr>
<tr>
<td>Central Hole Side</td>
<td>0.0383 m</td>
<td></td>
</tr>
<tr>
<td>Angular Structures</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Pin Diameter</td>
<td>0.0105 m</td>
<td></td>
</tr>
<tr>
<td>Pin Pitch (expanded)</td>
<td>0.0140 m</td>
<td></td>
</tr>
<tr>
<td>Side Angular Elements</td>
<td>0.0122 m</td>
<td></td>
</tr>
<tr>
<td>P/D Ratio</td>
<td>1.3333</td>
<td></td>
</tr>
<tr>
<td>FA Flow Area</td>
<td>0.047313 m²</td>
<td></td>
</tr>
<tr>
<td>Hydraulic Diameter</td>
<td>0.013267 m</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>POWER (BOC)</th>
<th>TOTAL ACTIVE POWER</th>
<th>1.482E+09 W</th>
</tr>
</thead>
<tbody>
<tr>
<td>INNER POWER</td>
<td>501.4E+6 W</td>
<td></td>
</tr>
<tr>
<td>INTERM POWER</td>
<td>489.2E+6 W</td>
<td></td>
</tr>
<tr>
<td>OUTER POWER</td>
<td>491.6E+6 W</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MASSFLOW</th>
<th>Cp</th>
<th>148.77 J/kg/K</th>
</tr>
</thead>
<tbody>
<tr>
<td>T Inlet</td>
<td>400 °C</td>
<td></td>
</tr>
<tr>
<td>T Outlet</td>
<td>480 °C</td>
<td></td>
</tr>
<tr>
<td>DT</td>
<td>80 °C</td>
<td></td>
</tr>
<tr>
<td>Mass Flowrate</td>
<td>124539 kg/s</td>
<td></td>
</tr>
</tbody>
</table>

Tab. 4 – ELSY Geometry and T/H Parameters
3.2 3D and 1D Results comparison

As a first assessment of the 3D core model, it has been carried out a benchmark case where the results are expected to be very similar to those of RELAP5 independent channel model. In particular, the 3D simulation of the open core has been carried out without taking into account the turbulent viscosity and with constant pressure boundary conditions both at core inlet and outlet. In this configuration the model provides almost the one-dimensional solution, since the effect of momentum and energy exchange among assemblies is widely negligible. To put in direct comparison the results obtained with the two codes, in the 3D model are considered the value referred only to the central nodes of each subassembly.

The Fig. 9 shows the comparison between the core outlet lead temperatures. It is possible to see that starting from the same thermal-hydraulic conditions e.g. pressure drop 0.92 bar, lead velocity 1.598 m/s, power produced 1482 MWth, etc., the temperatures calculated by RELAP5 are slightly higher of those obtained with the 3D model. The difference range from 0.2 to 1.9 degree and as a consequence of this the average temperature drop over the core calculated with the two models differs of about one degree. The discrepancy could be explained by a slight difference in lead density. In fact, the density calculated by RELAP5 respect the 3D model results underestimated of 130kg/m³ that corresponds to about 1% error in mass flowrate, hence in the ΔT over the core.

Fig. 9 – Comparison between outlet lead temperatures [°C]
The tridimensional code is able to investigate the pressure, velocity and temperature fields but since the model describes the reactor at assembly level, the sub-assembly composition is seen as an homogeneous medium. Hence, it is not provided of a pin thermal structure like RELAP5. In order to derive the temperature cladding field from the bulk lead temperature and power distribution the following formula has been implemented in the 3D model:

\[ T_{\text{clad}} = T_{\text{bulk}} + \frac{Q r_{\text{pellet}}^2}{2 h r_{\text{pin}}} \]

where \( Q \) is the volumetric heat generation and \( h \) is the heat transfer coefficient that could be determined by the definition of Nusselt number, \( Nu=hD/k \), where \( D \) is the characteristic dimension of the system and \( k \) is the thermal conductivity. Also in this case the Zhukov heat transfer correlation [15] has been taken as a reference for the evaluation of heat transfer coefficient \( h \).

The comparison of the clad temperatures, shown in Fig. 10, underlined the good agreement between the methods, the slight discrepancies of the order of two degrees are consequence of the discrepancies already mentioned in the lead temperatures.

![Fig. 10 – Comparison between maximum clad temperatures [°C]](image-url)
4. Evaluation of main 3D effects on core T/H simulation

The benchmark test described in previous chapter has aimed at verifying the coherence of the results obtained with the new tridimensional model and a well known thermal-hydraulic tool as RELAP5. To do this some simplifying options have been considered e.g. constant pressure at inlet and outlet, losing almost completely the characteristic tridimensional effects of the unwrapped option.

This chapter analyze the effect on the 3D simulation to introduce a simple LES turbulent model to consider the turbulent viscosity effect and then, to impose a non-uniform pressure boundary condition at core outlet. In this way, the capability of the 3D model developed to simulate a fully tridimensional behavior of the open core will be preliminary assessed.

4.1 Evaluation of turbulent viscosity effects

In a reactor like ELSY, the effect of the turbulence viscosity could be very important. In fact, due to the relative high velocities of the lead that pass through the core, the heat conduction in liquid metal still have an important role but the convection is the dominant heat transfer mechanism. Follow that the distribution of temperatures could be accurately predicted by using one-dimensional models along the convective streamlines. For this reason we should expect good agreement between the RELAP5 and the three-dimensional computations for highly forced flows but poor matching for flows where the main heat transfer mechanism is not convection.

A first evaluation of the turbulence energy exchange term, required by the LES model, has been based on some CFD simulation over limited subassembly regions [17, 18]. The introduction of a simple LES turbulence model has produced results that can be seen in Fig. 11 in comparison of those obtained in the previous RELAP5 calculation.

Fig. 11 – Effect of the turbulent viscosity
To improve the readability of the results, in Fig. 12 it is shown the comparison between core temperatures computed by the CFD model with and without LES model.

**Fig. 12 – Temperature comparison with and without LES turbulence model.**

With the introduction of the standard LES model, the temperature profile becomes smoother, thus reflecting the interaction between the fuel assemblies. Starting from the same boundary condition of uniform pressure at core inlet/outlet and temperature at inlet, the fluid motion remain mainly vertical and the velocity uniform in magnitude, however, as can be seen in the Fig. 12a, the maximum temperature computed is three degree lower compared to the case without LES. This is a not negligible result because the difference could increase in particular accident scenarios thus involving the safety aspects, first of all the reduction of the hotspot temperatures.

However these results must be considered only preliminary results since for a very accurate evaluation of the turbulence energy exchange term a sub-channel analysis is needed in order to introduce the correct parameters that define this behavior [16].
4.2 Evaluations of plenum distribution pressure effects

A radial differential pressure distribution has been introduced at the core outlet as a boundary conditions to simulate the influence of the global ELSY cooling system on the core behavior. As already mentioned in paragraph 2.3, the presence of cylindrical support structures of finger absorbers in the upper plenum introduce a differential pressure drop at core outlet, higher in the center lower in the core periphery, with consequence in whole reactor behavior, which could be of particular importance in case of open assembly.

In this case, where the outlet profile of pressure is not uniform and in addition the 3D power distribution is considered, the computation become fully three-dimensional. A parabolic axisymmetric profile of the outlet pressure distribution is imposed (see Fig. 7) both in 3D model and RELAP5 calculations. In case of the tridimensional simulation the velocity field changes direction and magnitude inside the core and the outflow temperature profile differs substantially from the RELAP5 model, as shown in Fig. 13.

In this figure one can see that the temperatures computed with the three-dimensional code are slightly lower in the inner zone and higher in the outer zone to those computed by using the RELAP5 model. In the Fig. 14a it can be seen that temperatures computed with the tridimensional code are consistently lower (eleven degree) in comparison of which obtained setting the constant outlet pressure.

Fig. 13 – Effect of outlet pressure distribution

This result does not show the relevant conservative character of the RELAP5 model and it has to be red considering the particular scenario simulated. The 3D power distribution described in the test is related to ELSY BOC conditions and is not representative of the situation during the most part of the reactor operation. In fact, in order to flatten as much as possible the power distribution during the entire fuel cycle, at BOC a relative higher power is produced in the
outer region respect in the inner one. During the burnup process the performance of this region become worse in favor of the innermost regions. Therefore, at BOC conditions to consider the pressure distribution at core outlet limit the maximum temperatures which is located in the outermost fuel assemblies. Since at EOC conditions there is a consistent change in power distribution among the fuel regions, which increases in the inner and intermediate zones and decreases in the outer one, the fuel temperatures already higher in the inner region are subjected to further increase in case of an independent channel simulation performed with RELAP5. This behavior highlights the character too conservative of the RELAP5 simulation that not suitable to smooth the lead temperature at the core outlet as calculated by the tridimensional model.

The Fig. 14b shows the magnitude of the velocity field, higher in the outermost region with a foreseeable minimum value in correspondence of the core Z axis. The Figs. 14c and 14d show the magnitude of X and Y axis velocity component. The subsequent Fig. 15 collects the temperature, velocity and pressure fields at core inlet (on the left) and core outlet (on the right).

These results are a clear example of how a fully three-dimensional thermal-hydraulic simulation of the ELSY open core could avoid unnecessary conservative approach in the design assessment and safety analysis that could have a negative impact on the economic feasibility of the reactor.

![Fig. 14 – Results of the non-uniform pressure outlet calculation](image-url)
CORE INLET

a) Relative temperature (400°C)

CORE OUTLET

b) Relative temperature (400°C)

c) Velocity
d) Velocity

e) Relative Pressure (bar)
f) Relative Pressure (bar)

Fig. 15 – Temperature, velocity and pressure at core inlet and outlet
5. Conclusions

Within the framework of the national AdP ENEA-MSE a simplified three-dimension numerical model of an open square lattice reactor core has been developed with the purpose to take into account the intermingled effects between assembly flows, thus limiting the conservative approach of the analysis in support to core design and safety study.

A preliminary assessment of the model has been performed by comparing its results with the T/H reactor core behavior predicted with a one-dimension independent channel model based on RELAP5 code. To this purpose the conceptual design of the LFR core developed in the framework of the ELSY EU collaborative project has been adopted as a reference.

This preliminary assessment comparing the 3D results obtained for a configuration where the model is expected to provide almost the one-dimensional solution, with the results obtained with the RELAP5 one-dimensional independent channels approach has been satisfactory. In fact, the slight differences between the lead temperatures calculated by two models are justified by slight differences in the lead physical property used.

In spite of the preliminary character of the results obtained with the 3D model, which still needs additional and relevant efforts for an accurate evaluation of the turbulence energy exchange term, the results obtained introducing a simple LES turbulence model and a pressure radial distribution outlet profile have been discussed against the results obtained with the RELAP5 separated channel model. These further tests have showed as a fully three-dimensional thermal-hydraulic simulation of the ELSY open core could avoid unnecessary conservative approach in the design assessment and safety analysis that could have a negative impact on the economic feasibility of the reactor.

6. References


Appendix A

CFD Program and Input

The appendix would present a brief description of the CFD code structure and a sample layout of the input files. To have a complete description of the physical/mathematical aspects involved and computational approach, see reference [3].

A.1 Generalities

The code is written in C++ and it is constituted by a main file (ex13.C) which calls all the necessary functions organized in five C++ classes. The five classes are:

- the class MGCase, defines input and output data flow;
- the class MG Gauss, defines Gaussian integration;
- the class MGMesh, defines the geometrical mesh;
- the class MG Sol, defines the Navier-Stokes equation solver;
- the class MG SolT, defines the energy equation solver.

A.2 The main file ex13.C

This file is the main program. It allocates all the needed classes and manages input and output flow. Each time step is solved inside the temporal loop. All the settings must be specified in the config.h file.

// C++ include files that we need
#include <iostream>
#include <algorithm>
#include <math.h>
#include <fstream>
#include <map>
#include "config/config.h"
// -------------------------------
#ifdef LIBMESHF
#include "libmesh.h"
#include "perf_log.h"
define Perf_logstart_event perf_log.start_event
define Perf_logstop_event perf_log.stop_event
#else
#define Perf_logstart_event (printf)
define Perf_logstop_event (printf)
#endif
// -------------------------------
#include <lastypes.h>
#include "MG Solver.h"
#include "MG SolverT.h"
#include "MG SolverSA.h"
#include "MG SolverCC.h"
```c
#include "MGMesh.h"
#include "MG Gauss.h"
#include "MG Case.h"
#include "config/data.h"

// ***********************************************************
// The main program.
// ***********************************************************
CODE DOCUMENTATION 65

int main(int argc, char** argv) {
    #ifdef LIBMESH
        // Initialize libMesh.
        libMesh::init(argc, argv);
        {
            // -------------------------------------------------
            PerfLog perf_log("NSE");
            #endif
            #ifdef GENCASE
                // ***********************************************************
                // Case Generation
                // ***********************************************************
                #ifndef RESTART
                    Perf_logstart_event("GenCase");
                    GenCase();
                    Perf_logstop_event("GenCase");
                #endif
                #endif
            // ***********************************************************
            // MGSolver begin
            fprintf(stderr,"\n Start MGSolver \n");
            Perf_logstart_event("Reading");
            // Reading ***************
            // Data -------------------
            printf(" Reading I Data:\n ");
            double dt = ND_TIME_STEP;
            unsigned int t_in=0;
            double time=0.;
            printf("n Nondimensional Numbers:\n ");
            printf(" Re = %e We = %e Fr = %e \n", RHOref*Uref*Lref/MU0,
                   RHOref*Uref*Uref*Lref/(SIGMA+1.e-6),
                   Uref*Uref/(9.81*Lref));
            fprintf(stderr," - \n *");
            // velocity fem -------------------
            unsigned int kng[3],kfem[3];
            // N of gaussian points in 1D,2D,3D
            kng[0]=3;kng[1]=9;kng[2]=27;
            // Fem element type in 1D,2D,3D
            // pressure fem ---------------------
            unsigned int kng1[3],kfem1[3];
            // N of gaussian points in 1D,2D,3D
            kng1[0]=3;kng1[1]=9;kng1[2]=27;
            // Fem element type in 1D,2D,3D
            kfem1[0]=2;kfem1[1]=4;kfem1[2]=8;
            // Gauss Reading -------------------------
            fprintf(stderr," \n Reading II Gauss:\n ");
            MGGauss *dgauss; dgauss=new MGGauss(kng,kfem);CODE DOCUMENTATION 66
dgauss->init(27);// hex27
```

MGauss *dgauss_p; dgauss_p=new MGauss(kng1,kfem1);
dgauss_p->init(8);// hex8
printf(" - \n * \n");
//Mesh ----------------
fprintf(stderr,"\n Reading III Geometry:: \n");
fprintf(stderr," Mesh: ");
MGMesh *mgmesh1; mgmesh1=new MGMesh(DIMENSION,gridn+1);
mgmesh1->init(FILE_MESH_CASE);
printf(" - \n *");
// Multigrid ------
MGSol *mgs=NULL;
#if defined NS_EQUATIONS
printf("\n Reading IV Navier-Stokes Operators:: \n");
printf(" Multigrid, Matrix, Prol and Restr: \n");
mgs=new MGSol(*mgmesh1,NoLevels);
mgs->MGReadOp();
printf(" - \n *\n");
#endif
MGSolSA *mgsSA=NULL;
#if defined TURBULENCE
printf("\n Reading Turbulence Operators:: \n");
printf(" Multigrid, Matrix, Prol and Restr: \n");
mgsSA=new MGSolSA(NoLevels);
mgsSA->MGReadOp(*mgmesh1,0);
mgsSA->InitVel(*mgmesh1,*mgs,dt);
printf(" - \n *\n");
#endif
MGSolT *mgsT=NULL;
#if defined T_EQUATIONS
printf("\n Reading V Energy Operators:: \n");
// Multigrid ------
printf(" Multigrid, Matrix, Prol and Restr: \n");
mgsT=new MGSolT(*mgmesh1,NoLevels);
mgsT->MGReadOp();
printf(" - \n *\n");
#endif
// Set up time cycle t=0 ***************
MGSolCC *mgcc=NULL;
#if defined NS_EQUATIONS
fprintf(stderr,"\n NS Initializing:: \n");
fprintf(stderr," Solution: ");
mgs->GenSol(NoLevels-1);
mgs->GenOldSol(NoLevels-1);
fprintf(stderr," -\n");
#endif
#if defined TURBULENCE
fprintf(stderr,"\n Turbulence Initialize:: ");
fprintf(stderr," Solution: ");
mgsSA->GenSol(*mgmesh1,NoLevels-1);
mgsSA->GenOldSol(NoLevels-1);
Code DOCUMENTATION 67
fprintf(stderr," -\n");
#endif
#ifdef NS_EQUATIONS
fprintf(stderr,"\n Rhs: ");
fprintf(stderr," -\n");
#endif
#ifdef TURBULENCE
fprintf(stderr,"\n Rhs: ");
fprintf(stderr," -\n");
#endif
#ifdef T_EQUATIONS
fprintf(stderr,"\n Rhs: ");
fprintf(stderr," -\n");
#endif
```c
#ifdef T_EQUATIONS
printf("n Energy Initilize:: ");
printf("n Solution: ");
mgsT->GenSol(NoLevels-1);
mgsT->GenOldSol(NoLevels-1);
printf(" - 
");
#endif
printf("n Case Initilize:: ");
MGCase *mcase=new MGCase(*mgmesh1, NoLevels, N_TIME_STEPS);
mcase->init_data();
#ifdef RESTART
printf("n Restart %d %g", RESTART, RESTARTIME);
mcase->read(*mgmesh1, *mgs, *mgcc, *mgsT, *mgsSA, RESTART, NoLevels-1);
t_in=RESTART;
time += RESTARTIME;
#endif
mcase->print(*mgmesh1, *mgs, *mgcc, *mgsT, *mgsSA, t_in, NoLevels-1);
printf(" - 
");
Perf_logstop_event("Reading");
// -------------------------------------------------------
// time loop
for (unsigned int t_step=t_in; t_step< N_TIME_STEPS+t_in; ++t_step) {
    // Let the system of equations know the current time.
    std::cout << "

*** Solving time step " << t_step+1 <<", time = " << time+ ND_TIME_STEP << " ***" << std::endl;
    // Let the system of equations know the current time.
    std::cout << std::endl << "n Turbulence solution 
" << std::endl;
    mgsSA->MGTimeStep(*mgmesh1, *dgauss, 0);
    #endif
    #ifdef T_EQUATIONS
    std::cout << std::endl << "n Energy Solution 
" << std::endl;
    mgsT->MGTimeStep(time, *mcase, *mgcc, *mgs, *dgauss, 0);
    #endif
    Perf_logstop_event("MG Solver");
    #endif
    #ifdef NS_EQUATIONS
    // solving V-cycle Multigrid
    printf("n Navier-Stokes solution: ");
    mgs->MGTimeStep(*mcase, *mgsT, *mgcc, *dgauss, *dgauss_p_time, t_step-t_in);
    #endif
    #ifdef TURBULENCECODE DOCUMENTATION 68
    std::cout << std::endl << "n Turbulence solution 
" << std::endl;
    mgsSA->MGTimeStep(*mgmesh1, *dgauss, 0);
    #endif
    #ifdef T_EQUATIONS
    std::cout << std::endl << "n Energy Solution 
" << std::endl;
    mgsT->MGTimeStep(time, *mcase, *mgcc, *mgs, *dgauss, 0);
    #endif
    Perf_logstop_event("MG Solver");
    // -------------------------------------------------------
    // print
    Perf_logstart_event("output");
    if ((t_step+1-t_in)%PRINT_STEP == 0)
        mcase->print(*mgmesh1, *mgs, *mgcc, *mgsT, *mgsSA, t_step+1, NoLevels-1);
    Perf_logstop_event("output");
    time += ND_TIME_STEP;
    // end time loop
    // clean --------------------------------
    if (mcase != NULL) delete mcase;
    if (mgcc != NULL) delete mgcc;
    if (mgsT != NULL) delete mgsT;
    if (mgs != NULL) delete mgs;
    if (mgsSA != NULL) delete mgsSA;
    #endif
    #ifdef T_EQUATIONS
    printf("n Energy Initilize:: ");
    printf("n Solution: ");
mgsT->GenSol(NoLevels-1);
mgsT->GenOldSol(NoLevels-1);
printf(" - 
");
#endif
printf("n Case Initilize:: ");
MGCase *mcase=new MGCase(*mgmesh1, NoLevels, N_TIME_STEPS);
mcase->init_data();
#ifdef RESTART
printf("n Restart %d %g", RESTART, RESTARTIME);
mcase->read(*mgmesh1, *mgs, *mgcc, *mgsT, *mgsSA, RESTART, NoLevels-1);
t_in=RESTART;
time += RESTARTIME;
#endif
mcase->print(*mgmesh1, *mgs, *mgcc, *mgsT, *mgsSA, t_in, NoLevels-1);
printf(" - 
");
Perf_logstop_event("Reading");
// -------------------------------------------------------
// time loop
for (unsigned int t_step=t_in; t_step< N_TIME_STEPS+t_in; ++t_step) {
    // Let the system of equations know the current time.
    std::cout << "

*** Solving time step " << t_step+1 <<", time = " << time+ ND_TIME_STEP << " ***" << std::endl;
    // Let the system of equations know the current time.
    std::cout << std::endl << "n Turbulence solution 
" << std::endl;
    mgsSA->MGTimeStep(*mgmesh1, *dgauss, 0);
    #endif
    #ifdef T_EQUATIONS
    std::cout << std::endl << "n Energy Solution 
" << std::endl;
    mgsT->MGTimeStep(time, *mcase, *mgcc, *mgs, *dgauss, 0);
    #endif
    Perf_logstop_event("MG Solver");
    #endif
    #ifdef NS_EQUATIONS
    // solving V-cycle Multigrid
    printf("n Navier-Stokes solution: ");
    mgs->MGTimeStep(*mcase, *mgsT, *mgcc, *dgauss, *dgauss_p_time, t_step-t_in);
    #endif
    #ifdef TURBULENCECODE DOCUMENTATION 68
    std::cout << std::endl << "n Turbulence solution 
" << std::endl;
    mgsSA->MGTimeStep(*mgmesh1, *dgauss, 0);
    #endif
    #ifdef T_EQUATIONS
    std::cout << std::endl << "n Energy Solution 
" << std::endl;
    mgsT->MGTimeStep(time, *mcase, *mgcc, *mgs, *dgauss, 0);
    #endif
    Perf_logstop_event("MG Solver");
    // -------------------------------------------------------
    // print
    Perf_logstart_event("output");
    if ((t_step+1-t_in)%PRINT_STEP == 0)
        mcase->print(*mgmesh1, *mgs, *mgcc, *mgsT, *mgsSA, t_step+1, NoLevels-1);
    Perf_logstop_event("output");
    time += ND_TIME_STEP;
    // end time loop
    // clean --------------------------------
    if (mcase != NULL) delete mcase;
    if (mgcc != NULL) delete mgcc;
    if (mgsT != NULL) delete mgsT;
    if (mgs != NULL) delete mgs;
    if (mgsSA != NULL) delete mgsSA;
```
if (mgmesh1 != NULL) delete mgmesh1;
if (dgauss != NULL) delete dgauss;
if (dgauss_p != NULL) delete dgauss_p;
#endif
}
return libMesh::close();
#endif
}

A.3 Configuration file config.h

The options that could be setup by user are reported in Tab.A1. The configuration file config.h is reported below.

<table>
<thead>
<tr>
<th>help</th>
<th>command</th>
<th>option</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D active</td>
<td>#define DIM2</td>
<td>1</td>
<td>3D simulation</td>
</tr>
<tr>
<td>Bound. integr. active</td>
<td>#define BOUNDARY</td>
<td>1</td>
<td>Boundary integration</td>
</tr>
<tr>
<td>NS equation active</td>
<td>#define NS_EQUATIONS</td>
<td>1</td>
<td>Solve the Navier-Stokes eqs</td>
</tr>
<tr>
<td>Energy equation active</td>
<td>#define T_EQUATIONS</td>
<td>1</td>
<td>Solve the Energy eqs</td>
</tr>
<tr>
<td>Restart time</td>
<td>#define RESTARTTIME</td>
<td>1.1</td>
<td>Initial time set to t = 1.1</td>
</tr>
<tr>
<td>Restart active</td>
<td>#define RESTART</td>
<td>10</td>
<td>Restart from file label 10</td>
</tr>
<tr>
<td>Case active</td>
<td>#define GENCASE</td>
<td>1</td>
<td>Generate the case files</td>
</tr>
<tr>
<td>libmesh active</td>
<td>#define LIBMESH</td>
<td>1</td>
<td>linking with libMesh lib</td>
</tr>
<tr>
<td>GMV graphics active</td>
<td>#define OUTGMV</td>
<td>1</td>
<td>output with GMV</td>
</tr>
<tr>
<td>Print step</td>
<td>#define PRINT_STEP</td>
<td>10</td>
<td>Print each 10 steps</td>
</tr>
<tr>
<td>Info active</td>
<td>#define PRINT_INFO</td>
<td>1</td>
<td>Print info after function execution</td>
</tr>
<tr>
<td>LX dimension</td>
<td>#define LX</td>
<td>2</td>
<td>Set the x-dimension LX =2</td>
</tr>
<tr>
<td>LY dimension</td>
<td>#define LY</td>
<td>2</td>
<td>Set the y-dimension LY =2</td>
</tr>
<tr>
<td>LZ dimension</td>
<td>#define LZ</td>
<td>2</td>
<td>Set the z-dimension LZ =2</td>
</tr>
</tbody>
</table>

Tab. A1 – Options available in config.h file

#ifndef _config_cfg
#define _config_cfg
// ****************************************************************************
// BASIC SETTINGS (DIM and Navier-Stokes+Energy
// ****************************************************************************
// space 2D or 3D ***********************
// DIM2= two-dimensional simulation (undef 3D)
//#define DIM2 1
// generate the boundary mesh
#define BOUNDARY 1
// 2d axisymmetric case
#define AXISYMX 1
// equation ******************************
// for NS simulations
#define NS_EQUATIONS 1
//for TURBULENCE 1
// ********************
// for Energy simulations
#define T_EQUATIONS 1
// ********************
//equation TWO_PHASE
// #define TWO_PHASE 1  
// #define REFLEV 3  
// #define INLEV 0  
#ifndef INLEV  
#define INLEV (REFLEV-1)  
#endif  

// ***************************************  
// restart and generation ****************************  
#define RESTARTIME 4.725  
#define RESTART 3600  
// gencase **************************************  
// #define GENCASE 1  
#define LIBMESHF 1  
// print **************************************************  
#define OUTGMV 1  
#define PRINT_STEP 50  
#define PRINT_INFO 1  
// dimension for internal cube generation  
#define LX 2.  
#define LY 2.  
#define LZ 2.  
// *********************************************************  
// 2D ( DIM2= defined = two-dimensional simulations )  
// *********************************************************  
#ifdef DIM2 // 2D dim=2 --------------------------------  
#define DIMENSION 2  
#define NX 32  
#define NY 32  
#define NZ 0  
// Integration **********************************************************  
#define GEN_GAUSS 1  
#define N_GAUSS 9  
#define FILE_GAUSS "fem/shape2D_0909.in"  
#define FILE_GAUSS_P "fem/shape2D_0904.in"  
// FEM Element **************************************************  
#define ELEM_FEM QUAD9  
#define NDOF_FEM 9  
#define ORDER_FEM SECOND  
#endif  
#define ELEM_P QUAD4  
#define NDOF_P 4  
#define ORDER_P FIRST  
#else  
#define NDOF_P 4  
#endif  
#define NDOF_FEM2D 3  
#define NDOF_P2D 2  
// *********************************************************  
// 3D ( DIM2= undefined = three-dimensional simulations )  
// *********************************************************  
#else // 3D dim=3 --------------------------------  
#define DIMENSION 3  
#define NX 32  
#define NY 32  
#define NZ 32  
// Integration **********************************************************  
#define GEN_GAUSS 1  
#define N_GAUSS 27  


#define N_GAUSS2D 9
#define FILE_GAUSS "fem/shape3D_2727.in"
#define FILE_GAUSS_P "fem/shape3D_2708.in"
#define FILE_GAUSS_P2D "fem/shape2D_0904.in"
#define FILE_GAUSS2D "fem/shape2D_0909.in"

// FEM Element *****************************************
#define ELEM_FEM HEX27
#define NDOF_FEM 27
#define NDOF_FEM2D 9
#define ORDER_FEM SECOND
#ifndef NS_EQUATIONS
#define ELEM_P HEX8
#define NDOF_P 8
#define NDOF_P2D 4
#define ORDER_P FIRST
#else
#define NDOF_P 8
#endif
#endif

// FILES
// ********************************************
#define FILE_MESH_READ "data_in/mesh.msh"
#define FILE_MESH_CASE "data_in/mesh.in"
#ifndef NS_EQUATIONS
#define FILE_DOFST_CASE "data_in/dofs.in"
#define FILE_OUT_U00 "output/velocity.gmv.00%d"
#define FILE_OUT_U0 "output/velocity.gmv.0%d"
#define FILE_OUT_U "output/velocity.gmv.%d"
#define FILE_OUT_P00 "output/pressure.gmv.00%d"
#define FILE_OUT_P0 "output/pressure.gmv.0%d"
#define FILE_OUT_P "output/pressure.gmv.%d"
#endif
#ifdef T_EQUATIONS
#define FILE_DOFST_CASE "data_in/dofsT.in"
#define FILE_OUT_T00 "output/temperature.gmv.00%d"
#define FILE_OUT_T0 "output/temperature.gmv.0%d"
#define FILE_OUT_T "output/temperature.gmv.%d"
#endif
#endif
A.3 Data file `data.h`

The parameters available for the end-users are summarized in Tab. A2 and Tab. A3. The data file `data.h` is reported below.

```
#ifndef __data_h__
#define __data_h__

// parameters *************************************

// time
#define ND_TIME_STEP 0.001
#define TIME 0.0
#define N_TIME_STEPS 4000

#define QHEAT 1.15e+8 // heat volume density source
#define DIRGX 0.0 // gravity x-direction
#define DIRGY 0.0 // gravity y-direction
#define DIRGZ 0.0 // gravity z-direction
```

**Tab. A2 – Parameters available in data.h file**

<table>
<thead>
<tr>
<th>command</th>
<th>value</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>#define ILUINIT</td>
<td>100</td>
<td>ILU decomposition each 100 steps</td>
</tr>
<tr>
<td>grid0</td>
<td>0</td>
<td>bottom grid level</td>
</tr>
<tr>
<td>grid1</td>
<td>1</td>
<td>top grid level</td>
</tr>
<tr>
<td>MaxIter</td>
<td>15</td>
<td>Iteration multigrid (max)</td>
</tr>
<tr>
<td>Eps</td>
<td>1e-6</td>
<td>residual accuracy</td>
</tr>
<tr>
<td>MGSolverId</td>
<td>MGIterId</td>
<td>Multigrid type</td>
</tr>
<tr>
<td>Gamma</td>
<td>2</td>
<td>Multigrid cycle (1=V cycle 2=W Cycle)</td>
</tr>
<tr>
<td>RestrtType</td>
<td>1</td>
<td>restriction operator(1, simple 2, weighted)</td>
</tr>
<tr>
<td>Nu1</td>
<td>8</td>
<td>Number of pre-smoothing iterations</td>
</tr>
<tr>
<td>Nu2</td>
<td>8</td>
<td>Number of post-smoothing iterations</td>
</tr>
<tr>
<td>Omega</td>
<td>0.98</td>
<td>Relaxation parameter for smoothing</td>
</tr>
<tr>
<td>SmoothProc</td>
<td>GMRESIter</td>
<td>Smoothing method</td>
</tr>
<tr>
<td>PrecondProc</td>
<td>ILUPrecond</td>
<td>Preconditioner</td>
</tr>
<tr>
<td>NuC</td>
<td>40</td>
<td>Number of iterations on coarsest grid</td>
</tr>
<tr>
<td>OmegaC</td>
<td>0.98</td>
<td>Relaxation parameter on coarsest grid</td>
</tr>
<tr>
<td>SolvProc</td>
<td>GMRESIter</td>
<td>Coarsest level iterative method</td>
</tr>
<tr>
<td>PrecondProcC</td>
<td>(PrecondProcType)NULL</td>
<td>Coarsest level preconditioner</td>
</tr>
</tbody>
</table>

**Tab. A3 – Parameters for multigrid available in data.h file**

```c
#ifndef __data_h__
#define __data_h__

// parameters ****************************************

// time
#define ND_TIME_STEP 0.001
#define TIME 0.0
#define N_TIME_STEPS 4000
```
#define VOF_SUBSTEP 1
// physics ****************************************
#define Uref 1.
#define Lref 1.
#define Tref 1000.
#define PI 3.141592653589793238
#define P_IN 36000.
#define T_IN 673.15
// fluid properties ----------------
// monophase
#define RHO0 11367.0
#define MU0 .0022
#define NUT .0
#define KAPP A0 15.8
#define PRT 0.9
#define CP0 147.3
#define KOMP0 0.
// 2nd phase
#define RHO1 1.0
#define MU1 0.1
#define KAPP A1 1.0
#define CP1 1.0
#define KOMP1 0.
// surface tension
#define SIGMA 0.0725
// Heat source
#define QHEAT 1.20249144e+8
// temperature function
#define RT 1.
// Gravity
#define DIRGX 0.
#define DIRGY 0.
#define DIRGZ 0.
// **********************************************************
// Multigrid parameters ************************************
// **********************************************************
#define ILUINIT 10
// Cycle controls ************************************
// grid0
const unsigned int grid0=0; // level 0
//define GRID0 0 // level 0
// gridn
const unsigned int gridn=1; // level n
// "Number of grid levels:
const unsigned int NoLevels=gridn+1;
// "Number of intervals:
// const size_t MaxNoInt = (size_t) n_int;
// "Maximum number of iterations (cycles )
const int MaxIter=15;
// Break off accuracy for the residual:
const double Eps=1.e-6;
// Cycle type ************************************
// Solution method (MLSolverId):
// 1. multigrid = MGIterId |
// Nested multigrid iterations? (1. yes 0. no) | type
// (NestedMG=0/1) | 1. V cycle
// 2. multigrid preconditioned CG = MGPCGIterId | 2. W Cycle
const IterIdType MLSolverId = MGIterId;
// Nested multigrid iterations? (1. yes 0. no)
const bool NestedMG = 0;
// Type of multigrid: (1. Y cycle 2. W Cycle)
const int Gamma = 2;
// number of multigrid iterations within one MGPCG step for case 2 (cycle)
const int NoMGIter = 1;
// Restriction/Projection
const int RestrType = 1;
// Smoothing no coarse
// Number of pre-smoothing iterations
const int Nu1 = 8;
// Number of post-smoothing iterations
const int Nu2 = 8;
// Relaxation parameter for smoothing:
const double Omega = 0.98;
const IterProcType SmoothProc = GMRESIter;
const IterProcType SmoothProc = Explicit;
// Preconditioning for smoothing iterations: (PrecondProcType)
// Preconditioning: 0. none = (PrecondProcType)NULL
const PrecondProcType PrecondProc = ILUPrecond;
// Coarse Grid
// Number of iterations on coarsest grid: ---
const int NuC = 40;
// "Relaxation parameter on coarsest grid: ---
const double OmegaC = 0.98;
// "Solution method on coarsest grid" ---
Iterative methods: 0. Vanka
  1. Jacobi = JacobiIter
  2. SOR forward = SORForwIter
  3. SOR backward = SORBackwIter
  4. SOR symmetric = SSORIter
  5. Chebyshev = ChebyshevIter
  6. CG = CGIter
  7. CGN = CGNIter
  8. GMRES(10) = GMRESIter
  9. BiCG = BiCGIter
 10. QMR = QMRIter
 11. CGS = CGSIter
 12. Bi-CGSTAB = BiCGSTABIter
 13. Test = TestIter
const IterProcType SmoothProc = GMRESIter;
//const IterProcType SmoothProc = Explicit;
// Preconditioning for smoothing iterations: (PrecondProcType)
// Preconditioning: 0. none = (PrecondProcType)NULL
// 1. Jacobi = JacobiPrecond
// 2. SSOR = SSORPrecond
// 3. ILU/ICH = ILUPrecond
//const PrecondProcType PrecondProc = ILUPrecond;
// Coarse Grid
// Number of iterations on coarsest grid: ---
const int NuC = 40;
// "Relaxation parameter on coarsest grid: ---
const double OmegaC = 0.98;
// "Solution method on coarsest grid" ---
Iterative methods: 0. Vanka
  a. RungeKutta4
  b.explicit
  1. Jacobi = JacobiIter
  2. SOR forward = SORForwIter
  3. SOR backward = SORBackwIter
  4. SOR symmetric = SSORIter
  5. Chebyshev = ChebyshevIter
  6. CG = CGIter
  7. CGN = CGNIter
A.4 Boundary conditions

In order to change the boundary conditions, it is necessary to edit the user part in the appropriate function. For pressure and velocity boundary conditions one must edit the function `void MGSol::GenBc(const unsigned int Level)` in the file `MGSolver3DNS.C` as shown below.

```cpp
/// Here is the space for user code contribution
// *********************************************
// boundary conditions box
if (zp < 0.001) { // top side (inlet)
  bc[Level][dof_u]=0; bc[Level][dof_v]=0;
  // inlet pressure p=p_in
  if (i<n_p_dofs) bc[Level][idx_dof[k+3*n_nodes]]=0;
}
if (zp > LZ-0.001) {// bottom side (outlet)
  bc[Level][dof_u]=0; bc[Level][dof_v]=0;
  // outlet pressure p=0
}
//symmetry
if (xp < 0.001) { // side 1
  bc[Level][dof_u]=0;
}
if (xp > LX-0.001) { // side 3
  bc[Level][dof_u]=0;
}
if (yp < 0.001) { // side2
  bc[Level][dof_v]=0; bc[Level][dof_u]=0;
}
if (yp > LY-0.001) { // side4
  bc[Level][dof_v]=0; bc[Level][dof_u]=0;
}
// *****************************************************
```

The vertex point \((xp, yp, zp)\) can be used to set all the necessary boundary conditions. The face middle point is also provided as \((xm, ym, zm)\).
For boundary conditions of the energy equation one must edit the function `void MGSol::GenBc(const unsigned int Level)` in the file `MGSolver3DT.C` as shown below.

```c
/// Here is the space for user code contribution
// ********************************************
// boundary conditions on a reactor
if (zp < 0.001) bc[Level][dof_u]=0;
// ********************************************
```

The same points are provided also for this equation.

**A.5 Initial conditions**

**Initial pressure velocity solution.** To set the initial solution in pressure and velocity it is necessary to edit the function `void MGSol::GenSol(const unsigned int Level)` inside the file `MG Solver3DNS.C`. Opening the mentioned file it can be found the initial solution $u = 0$ and $p$ which changes linearly from $P_IN$ to zero over the $z$-axis. Therefore in the appropriate part of the function:

```c
// *************************
/// Here is the space for user contribution
u_value =0.;
w_value =0.;
p_value=(P_IN/(RHOref*Uref*Uref))*(LZ-zp)/LZ;
// ************************
```

**Initial Energy solution.** To set the initial solution in temperature it is necessary to edit the function `void MGSolT::GenSol(const unsigned int Level)` inside the file `MG Solver3DT.C`. Opening the file there is a constant initial solution $T=T_IN/Tref$ over all the domain. The inlet temperature $T=T_IN$ and the reference temperature $T=Tref$, are defined in the file `config/data.h`. The reference temperature is actually $Tref = 1000$ in order to have temperature values in the range $0 \sim 1kK$ (mainly for graphical purposes). The user area of the file `MG Solver3DT.C` appear as follow:

```c
// *************************
/// Here is the space for user contribution
u_value =T_IN/Tref
// *************************
```

**A.6 Physical property dependence on temperature**

The code can run with lead properties that can be considered as a function of temperature. These functions are defined directly in the files where they are used. If the property law must be modified, it is necessary to change the inline functions at the top of the followings:
- `MG Solver3DNS.C` for the momentum equations; here are defined $\rho = \rho(T)$ and $\nu = \nu(T)$
- `MG Solver3DT.C` for the energy equation; here are defined $\rho = \rho(T)$, $\kappa = \kappa(T)$ and $Cp = Cp(T)$.
Furthermore, it has to be set `#define RT 1` in `data.h` in order to switch on temperature dependencies.

**A.7 Power distribution and pressure loss distribution**

The power distribution and the pressure loss distribution are set in the file `data.in`. The file looks like this:

```
Level 0 64
0 0.375 0.375 0.375 1.03 1
1 0.875 0.375 0.375 0.91 1
2 1.375 0.375 0.375 1.02 1
3 1.875 0.375 0.375 1.12 1
4 0.375 0.875 0.375 1.04 1
5 0.875 0.875 0.375 0.78 1
6 1.375 0.875 0.375 1.02 1
7 1.875 0.875 0.375 1.11 1
........
........
```

The file shows for each element: the element number, the x-coordinate, the y-coordinate, the z-coordinate, the value of the power distribution factor and the value of the pressure loss factor. The file can be generated by a program that is enclosed in the code named `datagen`. The direct editing is not very easy since there are at the level 1 more than 15000 elements. The file should be completed at all mesh levels.

In this sample the pressure loss distribution enclosed in the code is constant and equal to 1.
Appendix B

Input RELAP5

The RELAP5 input deck is attached. In particular, it is considered, the case with differential pressure drop at core outlet discussed in paragraph 4.2.

* INPUT ELSY WITH OUTLET PRESSURE DROPS

* BOC Conditions
* 100 new transnt
101 run
* 120 101010000 0.0 pb Pri
* 402 time 0 ge null 0.0 l
* 200 0.
201 200.0 1.e-7 0.01 3 1000 1000 1000
* 
*---------------------------------------------
301 cntrlvar 001 * Delta Tcore
302 cntrlvar 002 * Total DP CORE
303 cntrlvar 003 * Static DP CORE
304 cntrlvar 004 * Pressure Drop CORE

*---------------------------------------------
* 1200000 UP_plen snglvol
* area length vol. teta fi e.c. rho dh flags
1200101 20.0 1.0 0.0 0.0 90.0 0.5 4.e-5 0.0 00000
1200200 3 4.5e5 673.15
*
*
* 0910000 pbjun1 sngljun
* from vol. to vol. jun. area
0910101 120010000 090010000 0.0 0.0 0.0 0.00000000
* control flowf flowg int.v
0910201 0.0 0.0 0.0 0.0
*
*
* 0900000 tankarg3 tmdpvol
* area lung vol horz vert delz rug hyd flag
0900101 1000.0 1.e6 1.e9 0.0 90.0 1.0 0.0 0.0 10
0900200 3 * option default fluid (Pb)
* time press Temp.
0900201 0.0 4.5e5 753.16
*
*************************************************************************
*
* 1000000 L_plen snglvol
* area length vol. teta fi e.c. rho dh flags
*1000101 29.21 1.0 0.0 0.0 90.0 1.0 4.e-5 0.0 00000
1000101 129.21  1.0  0.0  0.0  90.  1.0  4.0e-5  0.0  00000
1000200  3  9.0e5  673.16
*
*
0810000 wat tmdpjun
* from vol. to vol.  jun. area
0810101 080010000 100000000 0.0
* control  flowf  flowg  int.v
0810200 1
0810201 0.0   0.0   0.0   0.
*0810202 10.0  31135.0   0.0   0.
0810202 10.0  31650.0   0.0   0.
*
*
0800000 low-ic tmdpvol
* area  lung  vol  horz  delz  rug  hyd  flag
0800101 0.0  1.  1.e6  0.0  90.0  1.0  0.0  0.0  0.00000
0800200 3 * option default fluid (Pb)
* time  press  Temp.
0800201 0.0  9.0e5  673.16
*
*
*==================================== LOWER JUNCTIONS INNER ZONE ================
*====================================
*1310000 LjunA112 sngljun
* from vol. to vol.  area  flc  rlc  flag
1310101 100010000 101000000 0.0  2.1  1.0  00000000
* control  flowf  flowg  int.v
1310201 0.0   0.0   0.0   0.0
*
*
*
*
*==================================== UPPER JUNCTIONS INNER ZONE ================
*====================================
*1610000 UjunA122 sngljun
* from vol. to vol.  area  flc  rlc  flag
1610101 100010000 117000000 0.0  2.1  1.0  00000000
1610201 0.0   0.0   0.0   0.0
*
<table>
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<th>Rev.</th>
<th>Distrib.</th>
<th>Pag.</th>
<th>Sigla di identificazione</th>
<th>data1</th>
<th>data2</th>
<th>data3</th>
<th>data4</th>
<th>data5</th>
<th>data6</th>
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<th>data8</th>
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<th>data10</th>
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<td></td>
<td></td>
<td>0</td>
<td>R</td>
<td>36</td>
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```
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<tr>
<th>control</th>
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<th>int.v</th>
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<td>1610101</td>
<td>101010000 120000000 0.0</td>
<td>1.9565 0.5 00000000</td>
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<tr>
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<th></th>
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<tr>
<td>1620000</td>
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<td>1620101</td>
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<td>1.9565 0.5 00000000</td>
<td></td>
</tr>
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<tr>
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<td>sngljun</td>
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<td>1630101</td>
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<td>sngljun</td>
<td></td>
</tr>
<tr>
<td>1780101</td>
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<td></td>
</tr>
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<td>pipe</td>
<td></td>
</tr>
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<td>1010001</td>
<td>16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1010101</td>
<td>0.023657 16</td>
<td>* flow area</td>
<td></td>
</tr>
<tr>
<td>1010301</td>
<td>0.2</td>
<td>4</td>
<td>* volume height</td>
</tr>
<tr>
<td>1010302</td>
<td>0.1</td>
<td>5</td>
<td>* volume height</td>
</tr>
<tr>
<td>1010303</td>
<td>0.09</td>
<td>15</td>
<td>* volume height</td>
</tr>
<tr>
<td>1010304</td>
<td>0.2</td>
<td>16</td>
<td>* volume height *total FA height=1945mm</td>
</tr>
<tr>
<td>1010401</td>
<td>0.0</td>
<td>16</td>
<td>* volume of node</td>
</tr>
<tr>
<td>1010501</td>
<td>0.0</td>
<td>16</td>
<td>* horizontal angle</td>
</tr>
<tr>
<td>1010601</td>
<td>90.0</td>
<td>16</td>
<td>* vertical angle</td>
</tr>
<tr>
<td>1010701</td>
<td>0.2</td>
<td>4</td>
<td>* elevation change</td>
</tr>
<tr>
<td>1010702</td>
<td>0.1</td>
<td>5</td>
<td>* elevation change</td>
</tr>
<tr>
<td>1010703</td>
<td>0.09</td>
<td>15</td>
<td>* elevation change</td>
</tr>
<tr>
<td>1010704</td>
<td>0.2</td>
<td>16</td>
<td>* elevation change</td>
</tr>
<tr>
<td>1010801</td>
<td>3.0e-6 0.013267 16</td>
<td>* friction factor - roughness</td>
<td></td>
</tr>
<tr>
<td>1010901</td>
<td>0.0</td>
<td>1</td>
<td>* concentrated loss coeff.</td>
</tr>
<tr>
<td>1010902</td>
<td>0.0</td>
<td>2</td>
<td>* concentrated loss coeff.</td>
</tr>
<tr>
<td>1010903</td>
<td>0.0</td>
<td>3</td>
<td>* concentrated loss coeff.</td>
</tr>
<tr>
<td>1010904</td>
<td>0.0</td>
<td>4</td>
<td>* concentrated loss coeff.</td>
</tr>
<tr>
<td>1010905</td>
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<td>* concentrated loss coeff.</td>
</tr>
<tr>
<td>1010906</td>
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<td>6</td>
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</tr>
<tr>
<td>1010907</td>
<td>0.52</td>
<td>7</td>
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</tr>
<tr>
<td>1010908</td>
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<tr>
<td>1010909</td>
<td>0.52</td>
<td>9</td>
<td>* concentrated loss coeff.</td>
</tr>
<tr>
<td>1010910</td>
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<td>10</td>
<td>* concentrated loss coeff.</td>
</tr>
<tr>
<td>1010911</td>
<td>0.52</td>
<td>11</td>
<td>* concentrated loss coeff.</td>
</tr>
<tr>
<td>1010912</td>
<td>0.0</td>
<td>12</td>
<td>* concentrated loss coeff.</td>
</tr>
<tr>
<td>1010913</td>
<td>0.52</td>
<td>13</td>
<td>* concentrated loss coeff.</td>
</tr>
<tr>
<td>1010914</td>
<td>0.0</td>
<td>14</td>
<td>* concentrated loss coeff.</td>
</tr>
<tr>
<td>1010915</td>
<td>0.52</td>
<td>15</td>
<td>* concentrated loss coeff.</td>
</tr>
</tbody>
</table>
```
1011001 0000000 16 * volume flags
1011101 00100000 15 * junction flags
1011201 003 8.00e5 673.16 0.0 0.0 0.0 16
1011300 0
1011301 0.0 0.0 0.0 15 *

1020000 INN_A122 pipe
1020001 16
1020101 0.023657 16 * flow area
1020301 0.2 4 * volume height
1020302 0.1 5 * volume height
1020303 0.09 15 * volume height
1020304 0.2 16 * volume height *total FA height=1945mm
1020401 0.0 16 * volume of node
1020501 0.0 16 * horizontal angle
1020601 90.0 16 * vertical angle
1020701 0.2 4 * elevation change
1020702 0.1 5 * elevation change
1020703 0.09 15 * elevation change
1020704 0.2 16 * elevation change
1020801 3.0e-6 0.013267 16 * friction factor - roughness
1020901 0.0 0.0 1 * concentrated loss coeff.
1020902 0.0 0.0 2 * concentrated loss coeff.
1020903 0.0 0.0 3 * concentrated loss coeff.
1020904 0.0 0.0 4 * concentrated loss coeff.
1020905 0.0 0.0 5 * concentrated loss coeff.
1020906 0.0 0.0 6 * concentrated loss coeff.
1020907 0.52 0.0 7 * concentrated loss coeff.
1020908 0.0 0.0 8 * concentrated loss coeff.
1020909 0.52 0.0 9 * concentrated loss coeff.
1020910 0.0 0.0 10 * concentrated loss coeff.
1020911 0.52 0.0 11 * concentrated loss coeff.
1020912 0.0 0.0 12 * concentrated loss coeff.
1020913 0.52 0.0 13 * concentrated loss coeff.
1020914 0.0 0.0 14 * concentrated loss coeff.
1020915 0.52 0.0 15 * concentrated loss coeff.
1021001 0000000 16 * volume flags
1021101 00100000 15 * junction flags
1021201 003 8.00e5 673.16 0.0 0.0 0.0 16
1021300 0
1021301 0.0 0.0 0.0 15 *

[skip]

1180000 INN_A612 pipe
1180001 16
1180101 0.023657 16 * flow area
1180301 0.2 4 * volume height
1180302 0.1 5 * volume height
1180303 0.09 15 * volume height
1180304 0.2 16 * volume height *total FA height=1945mm
1180401 0.0 16 * volume of node
1180501 0.0 16 * horizontal angle
1180601 90.0 16 * vertical angle
1180701 0.2 4 * elevation change
1180702 0.1 5 * elevation change
1180703 0.09  15  * elevation change
1180704 0.2   16  * elevation change
1180801 3.0e-6 0.013267 16  * friction factor - roughness
1180901 0.0   0.0   1  * concentrated loss coeff.
1180902 0.0   0.0   2  * concentrated loss coeff.
1180903 0.0   0.0   3  * concentrated loss coeff.
1180904 0.0   0.0   4  * concentrated loss coeff.
1180905 0.0   0.0   5  * concentrated loss coeff.
1180906 0.0   0.0   6  * concentrated loss coeff.
1180907 0.52  0.0   7  * concentrated loss coeff.
1180908 0.0   0.0   8  * concentrated loss coeff.
1180909 0.52  0.0   9  * concentrated loss coeff.
1180910 0.0   0.0  10  * concentrated loss coeff.
1180911 0.52  0.0  11  * concentrated loss coeff.
1180912 0.0   0.0  12  * concentrated loss coeff.
1180913 0.52  0.0  13  * concentrated loss coeff.
1180914 0.0   0.0  14  * concentrated loss coeff.
1180915 0.52  0.0  15  * concentrated loss coeff.
1181001 0000000 16  * volume flags
1181101 00100000 15  * junction flags
1181201 003 8.00e5 673.16 0.0 0.0 0.0 16
1181300 0
1181301 0.0 0.0 0.  15  *

*============================================================================*
*================= LOWER JUNCTIONS INTERMEDIATE ZONE =========================*
*============================================================================*

2310000 LjunA162 sngljun
  * from vol. to vol.  area  flc  rlc  flag
2310101 100010000  201000000 0.0  2.1   1.0   00000000
  * control  flowf  flowg  int.v
2310201 0.0  0.0   0.0  0.0

2320000 LjunA25 sngljun
2320101 100010000  202000000 0.0  2.1   1.0   00000000
2320201 0.0  0.0   0.0  0.0

2330000 LjunA26 sngljun
2330101 100010000  203000000 0.0  2.1   1.0   00000000
2330201 0.0  0.0   0.0  0.0

*============================================================================*
*================= UPPER JUNCTIONS INTERMEDIATE ZONE =========================*
*============================================================================*

2420000 LjunA64 sngljun
2420101 100010000  212000000 0.0  2.1   1.0   00000000
2420201 0.0  0.0   0.0  0.0

2430000 LjunA71 sngljun
2430101 100010000  213000000 0.0  2.1   1.0   00000000
2430201 0.0  0.0   0.0  0.0

*============================================================================*
*=================================================================================
*============================================================================*
**PIPED INTERMEDIATE ZONE**

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<thead>
<tr>
<th>Pipe ID</th>
<th>Flow Area</th>
<th>Area Flow</th>
<th>Flow Node</th>
<th>Int. Vertical</th>
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<tr>
<td>INT_A162</td>
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<td>120000000</td>
<td>0.0</td>
<td>1.6938</td>
</tr>
<tr>
<td>INT_A162</td>
<td>0.00000000</td>
<td>120000000</td>
<td>0.0</td>
<td>1.6938</td>
</tr>
<tr>
<td>INT_A162</td>
<td>0.00000000</td>
<td>120000000</td>
<td>0.0</td>
<td>1.6938</td>
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**Concentrated Loss Coefficients**

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<tr>
<td>0.00000000</td>
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**Friction Factor - Roughness**

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3350000  Ljun_A_83  sngljun
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* ...............................................................
* ============== UPPER JUNCTIONS OUTER ZONE ===============
* ...............................................................

3610000  Ujun_A172  sngljun
*  from vol.    to vol.     area   flc   rlc   flag
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3610201  0.0          0.0         0.0          0.0

3620000  Ujun_A_27  sngljun
3620101  302010000  120000000  0.0    1.1791 0.5   00000000
3620201  0.0          0.0         0.0          0.0

3630000  Ujun_A_28  sngljun
3630101  303010000  120000000  0.0    1.1791 0.5   00000000
3630201  0.0          0.0         0.0          0.0

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3740201  0.0          0.0         0.0          0.0

3750000  Ujun_A_83  sngljun
3750101  315010000  120000000  0.0    1.1791 0.5   00000000
3750201  0.0          0.0         0.0          0.0

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* ================ PIPES OUTER ZONE ================
* ...............................................................

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3150000 OUT_A_83 pipe 
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3150101 0.047313 16 * flow area 
3150301 0.2 4 * volume height 
3150302 0.1 5 * volume height 
3150303 0.09 15 * volume height 
3150304 0.2 16 * volume height *total FA height=1945mm 
3150401 0.0 16 * volume of node 
3150501 0.0 16 * horizontal angle 
3150601 90.0 16 * vertical angle 
3150701 0.2 4 * elevation change 
3150702 0.1 5 * elevation change 
3150703 0.09 15 * elevation change 
3150704 0.2 16 * elevation change 
3150801 3.0e-6 0.013267 16 * friction factor - roughness 
3150901 0.0 0.0 1 * concentrated loss coeff. 
3150902 0.0 0.0 2 * concentrated loss coeff. 
3150903 0.0 0.0 3 * concentrated loss coeff. 
3150904 0.0 0.0 4 * concentrated loss coeff. 
3150905 0.0 0.0 5 * concentrated loss coeff. 
3150906 0.0 0.0 6 * concentrated loss coeff. 
3150907 0.52 0.0 7 * concentrated loss coeff. 

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3150909 0.52 0.0 9 * concentrated loss coeff.
3150910 0.0 0.0 10 * concentrated loss coeff.
3150911 0.52 0.0 11 * concentrated loss coeff.
3150912 0.0 0.0 12 * concentrated loss coeff.
3150913 0.52 0.0 13 * concentrated loss coeff.
3150914 0.0 0.0 14 * concentrated loss coeff.
3150915 0.52 0.0 15 * concentrated loss coeff.
3151001 0000000 16 * volume flags
3151101 00100000 15 * junction flags
3151201 003 8.00e5 673.16 0.0 0.0 0.0 16
3151300 0
3151301 0.0 0.0 0. 15 *

*===============================================================*
*===================== HEAT STRUCTURE CORE =====================*
*======================= INNER ZONE ===============================*

*===============================================================*
Centro Ricerche Bologna

Sigla di identificazione
FPN – P9LU – 025
Rev. 0
Distrib. R
Pag. di 44 51

11021704 102 1.10010e-01 0.0 0.0 4
11021705 102 1.14410e-01 0.0 0.0 5
11021706 102 1.13892e-01 0.0 0.0 6
11021707 102 1.09049e-01 0.0 0.0 7
11021708 102 1.01844e-01 0.0 0.0 8
11021709 102 9.05869e-02 0.0 0.0 9
11021710 102 7.71503e-02 0.0 0.0 10
11021900 1
11021901 0.013267 100. 100. 0. 0. 0. 0. 1. 1. 1.3333 1. 10
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[skip]

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11181000 10 19 21 0.0 0 1 32
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11181202 2 15
11181203 3 18
11181301 1. 12
11181302 0. 18
11181400 0
11181401 673.16 19
11181501 0 0 0 1 19.26 10
11181601 118060000 100 110 1 19.26 10
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11181710 118 7.71503e-02 0.0 0.0 10
11181900 1
11181901 0.013267 100. 100. 0. 0. 0. 0. 1. 1. 1.3333 1. 10
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*=================================================================
*====================== INTERMEDIATE ZONE ==========================
*=================================================================
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12011202 2 15
12011203 3 18
12011301 1. 12
12011302 0. 18
12011400 0
12011401 673.16 19
12011501 0 0 0 1 19.26 10
12011601 201060000 100 110 1 19.26 10
12011701 201 8.48697e-02 0.0 0.0 1
12011702 201 9.63043e-02 0.0 0.0 2
12011703 201 1.06399e-01 0.0 0.0 3
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12011709  201  8.55096e-02  0.0  0.0  9
12011710  201  7.07905e-02  0.0  0.0  10
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*
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[skip]
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12131101  12 4.5e-3  3 4.65e-3  3 5.25e-3
12131201  1  12
12131202  2  15
12131203  3  18
12131301  1.  12
12131302  0.  18
12131400  0
12131401  673.16  19
12131501  0  0  0  1 38.52  10
12131601  213060000  10000  110 1 38.52  10
12131701  213  8.48697e-02  0.0  0.0  1
12131702  213  9.63034e-02  0.0  0.0  2
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12131706  213  1.15623e-01  0.0  0.0  6
12131707  213  1.10313e-01  0.0  0.0  7
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12131709  213  8.55096e-02  0.0  0.0  9
12131710  213  7.07905e-02  0.0  0.0  10
12131900  1
12131901  0.013267  100. 100.  0. 0. 0. 0.  1. 1.  1.3333  1. 10
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*==================================================================*
* HEAT STRUCTURE CORE *==================================================================*
*==================================================================*
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13011100  0 1
13011101  12 4.5e-3  3 4.65e-3  3 5.25e-3
13011201  1  12
13011202  2  15
13011203  3  18
13011301  1.  12
13011302  0.  18
13011400  0
13011401  673.16  19
13011501  0  0  0  1 19.26  10
13011601  301060000  10000  110 1 19.26  10
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13011702  301  9.52704e-02  0.0  0.0  2
13011703  301  1.06801e-01  0.0  0.0  3
13011704 301 1.14484e-01 0.0 0.0 4
13011705 301 1.17922e-01 0.0 0.0 5
13011706 301 1.16983e-01 0.0 0.0 6
13011707 301 1.10469e-01 0.0 0.0 7
13011708 301 1.00793e-01 0.0 0.0 8
13011709 301 8.63532e-02 0.0 0.0 9
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13011900 1
13011901 0.013267 100. 100. 0. 0. 0. 0. 1.1. 1.3333 1.10
*
[skip]
*
13151000 10 19 2 1 0.0 0 1 32
13151100 0 1
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13151202 2 15
13151203 3 18
13151301 1. 12
13151302 0. 18
13151400 0
13151401 673.16 19
13151501 0 0 0 1 38.52 10
13151601 315060000 10000 110 1 38.52 10
13151701 315 8.33685e-02 0.0 0.0 1
13151702 315 9.52704e-02 0.0 0.0 2
13151703 315 1.06801e-01 0.0 0.0 3
13151704 315 1.14484e-01 0.0 0.0 4
13151705 315 1.17922e-01 0.0 0.0 5
13151706 315 1.16983e-01 0.0 0.0 6
13151707 315 1.10469e-01 0.0 0.0 7
13151708 315 1.00793e-01 0.0 0.0 8
13151709 315 8.63532e-02 0.0 0.0 9
13151710 315 6.75547e-02 0.0 0.0 10
13151900 1
13151901 0.013267 100. 100. 0. 0. 0. 0. 1.1. 1.3333 1.10
*

************** POWER TABLES INNER ZONE ***************

*** FA 1-1/2
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20210100 power 402 1. 4302795.7
20210101 -1.0 0.0
20210102 0.0 0.0
20210103 20.0 1.0 *100%
20210104 3000.0 1.0
*

*** FA 1-2/2
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20210202 0.0 0.0
20210203 20.0 1.0 *100%
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******* POWER TABLES OUTER ZONE **************

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** CONTROL VARIABLES **

** Delta T core **

- Delta TCR sum 1. 0.0 1
- tempf 120010000
- tempf 100010000

** Total DP Core **

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* Static DP CORe *

20500300  rhogAVGc  sum  9.81  306705.1
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20500302  0.2  rhof  101020000
20500303  0.2  rhof  101030000
20500304  0.2  rhof  101040000
20500305  0.15  rhof  101050000
20500306  0.09  rhof  101060000
20500307  0.09  rhof  101070000
20500308  0.09  rhof  101080000
20500309  0.09  rhof  101090000
20500310  0.09  rhof  101100000
20500311  0.09  rhof  101110000
20500312  0.09  rhof  101120000
20500313  0.09  rhof  101130000
20500314  0.09  rhof  101140000
20500315  0.09  rhof  101150000
20500316  0.1  rhof  101160000
20500317  0.5  rhof  100010000
20500318  0.5  rhof  120010000

* DP over the CORE*

20500400  DelAVGkc  sum  1.0  30271.751
20500401  0.0  1.0  p  100010000
20500402  -1.0  p  120010000
20500403  -1.0  cntrlvar  003

* MATERIAL TABLE *

20100100  tbl/fctn  1  1 * Fuel
20100200  tbl/fctn  1  1 * Gap
20100300  tbl/fctn  1  1 * Clad

* uo2 conductivity (w/m/k) *

20100101  3. 8.361
20100102  366. 7.46
20100103  373. 7.37
20100104  473. 6.32
20100105  533. 5.82
20100106  573. 5.53
20100107  623. 5.20
20100108  673. 4.91
20100109  723. 4.65
20100110  773. 4.42
20100111  823. 4.21
20100112  873. 4.02
20100113  923. 3.85
20100114  973. 3.69
20100115  1023. 3.55
20100116  1073. 3.42
20100117  1123. 3.29
20100118  1223. 3.08
20100119 1273. 2.99
20100120 1323. 2.91
20100121 1373. 2.83
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20100123 1473. 2.69
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20100125 1573. 2.59
20100126 1623. 2.54
20100127 1673. 2.50
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20100129 1823. 2.41
20100130 1873. 2.39
20100131 1923. 2.38
20100132 1973. 2.37
20100133 2023. 2.37
20100134 2073. 2.37
20100135 2123. 2.37
20100136 2173. 2.38
20100137 2223. 2.40
20100138 2273. 2.42
20100139 2323. 2.44
20100140 2423. 2.51
20100141 2473. 2.55
20100142 2523. 2.59
20100143 2573. 2.64
20100144 2623. 2.69
20100145 2673. 2.75
20100146 2723. 2.89
20100147 2823. 2.96
20100148 2873. 3.04
20100149 4200. 7.35

* heat capacity (j/m3/k)

20100151 3. 2.98e6
20100152 500. 2.98e6
20100153 1000. 3.34e6
20100154 1500. 3.42e6
20100155 2000. 3.84e6
20100156 2500. 5.14e6
20100157 3000. 5.24e6

* gap conductivity (w/m/k)
* (PDS-XADS value to be revised)
20100201 3. 0.38
20100202 5000. 0.38

* heat capacity (j/m3/k)
* (PDS-XADS value to be revised)
20100251 3. 5.40
20100252 5000. 5.40

* stainless steel conductivity (w/m/k)
* from Sobolev doc. for T91
20100301 3. 24.16
20100302 300. 24.16
20100303 350. 24.95
20100304 400. 25.66
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* " heat capacity (j/m³/k)
* from Sobolev doc. for T91

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