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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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Marzo 2009

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/reflector 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/reflector 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.
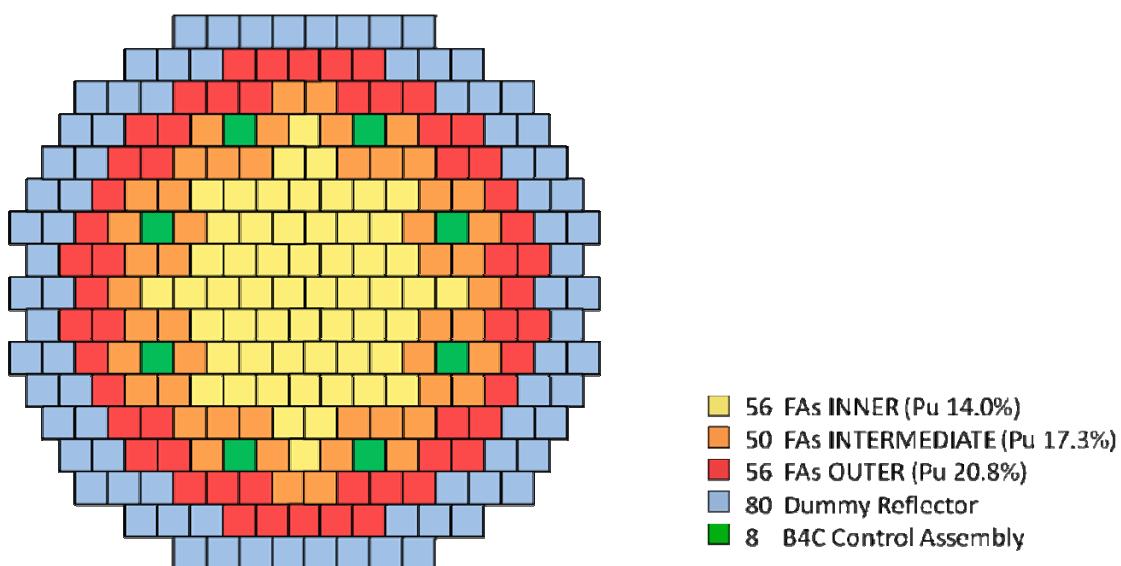
Fig. 1 – Scheme of ELSY core.

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.
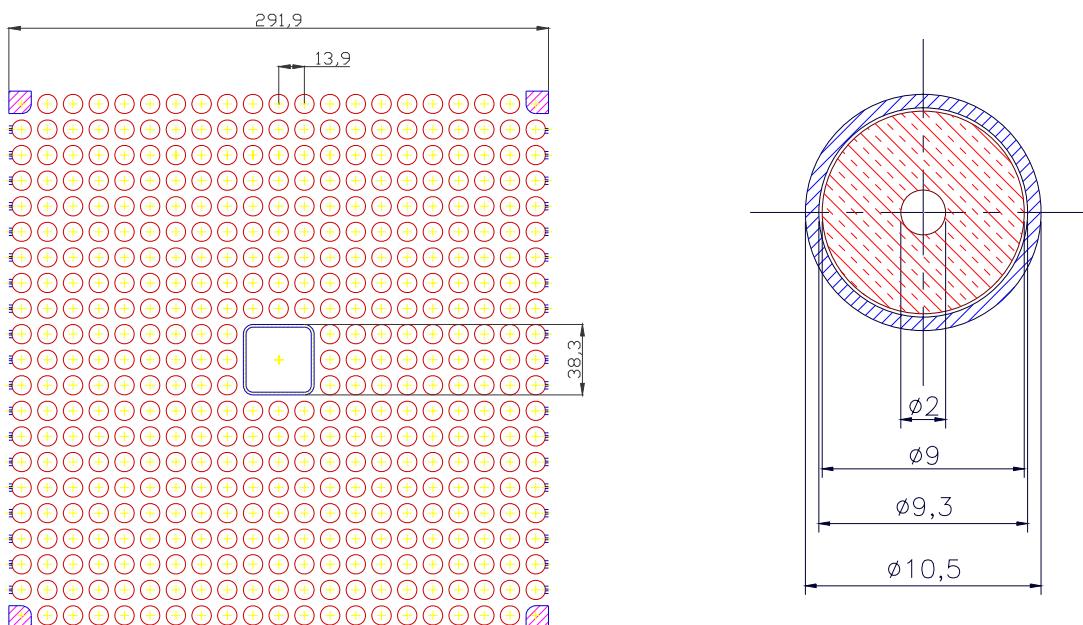
Fig. 2 – Design and dimensions [mm] of fuel assembly and fuel pin.

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.
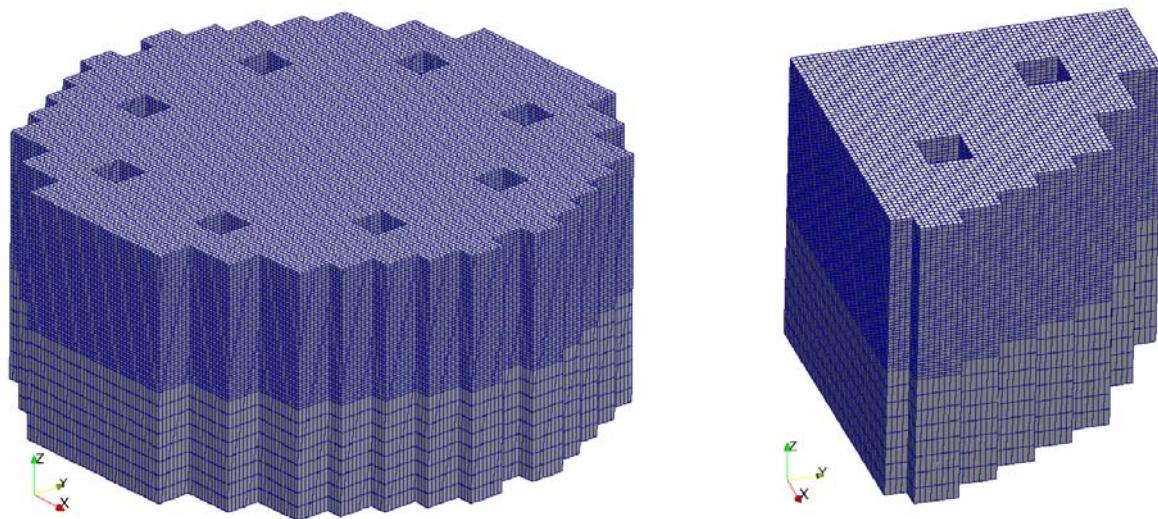
Fig. 3 – Full reactor and computational domain

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.

	area (m^2)
Pin area	370.606 × 10−4
Corner box area	5.717 × 10−4
Central box beam	2.092 × 10−4
Channel central box beam area	12.340 × 10−4
Coolant area	473.605 × 10−4
Assembly area	864.360 × 10−4
Coolant/Assembly ratio	0.548

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.
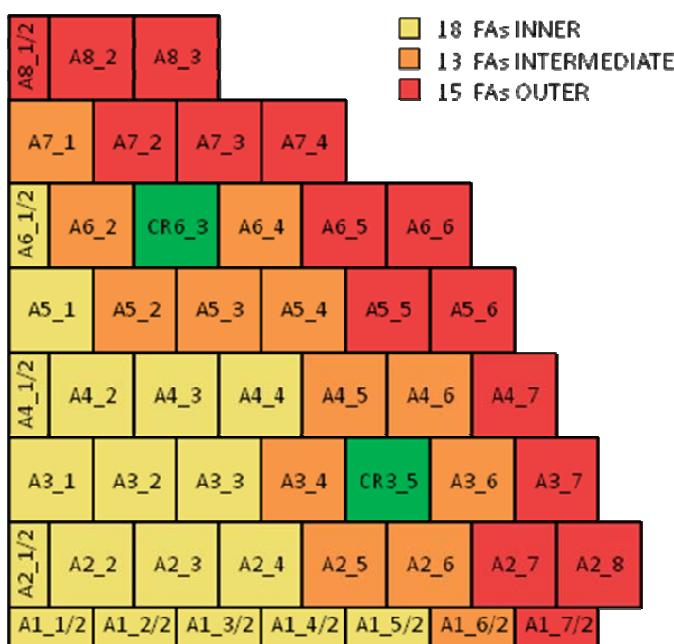
TABLE OF POWER [MW]					
INNER		**INTERMEDIATE**		**OUTER**	
A11/2*	8.606	A16/2*	10.775	A17/2*	10.036
A12/2*	8.801	A2_5	10.188	A2_7	10.908
A13/2*	9.043	A2_6	10.269	A2_8	7.842
A14/2*	9.301	A3_4	9.943	A3_7	8.465
A15/2*	9.560	A3_6	9.249	A4_7	8.520
A21/2*	8.678	A4_5	10.132	A5_5	10.962
A2_2	8.759	A4_6	9.399	A5_6	8.621
A2_3	8.943	A5_2	9.696	A6_5	9.766
A2_4	9.112	A5_3	9.857	A6_6	7.776
A3_1	8.811	A5_4	10.400	A7_2	9.746
A3_2	8.921	A6_2	9.410	A7_3	8.833
A3_3	9.071	A6_4	9.057	A7_4	7.699
A41/2*	8.850	A7_1	9.318	A81/2*	8.029
A4_2	8.903			A8_2	7.806
A4_3	9.043			A8_3	6.922
A4_4	9.218				
A5_1	8.790				
A61/2*	8.725				

(*) Power referred to the entire fuel assembly

Fig. 4 – Scheme and labeling of reactor modeled and power generated in each FA

The subsequent Tab. 2 summarize 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.

	Power [MWth]	#FA	P_avg [MWth]	ffrad
INNER	501.41	56	8.95	1.07
INTERMEDIATE	489.23	50	9.78	1.10
OUTER	491.60	56	8.78	1.25
TOTAL	1482.24	162	9.15	

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.
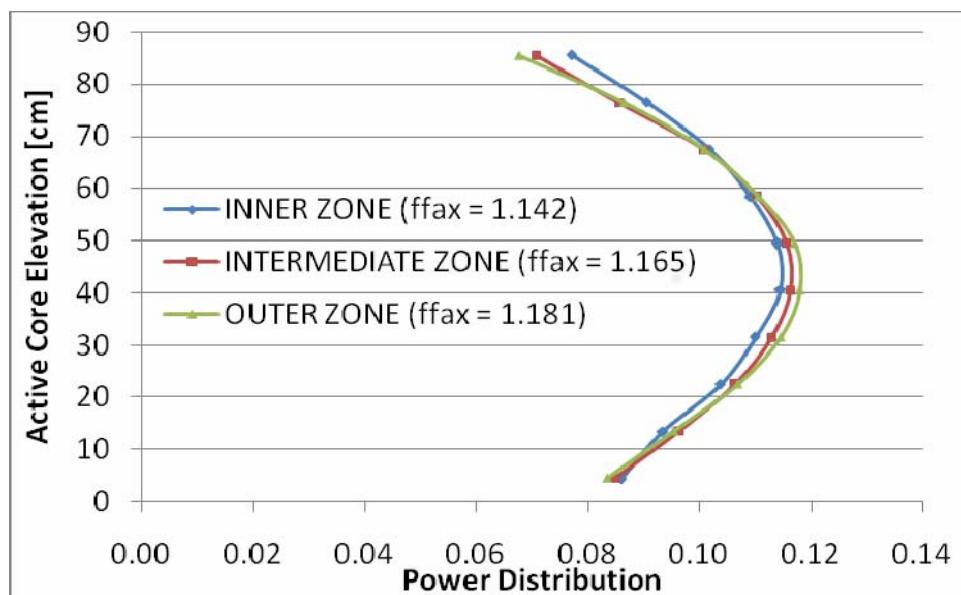
Fig. 5 – Axial Power Distributions and Form Factor

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.

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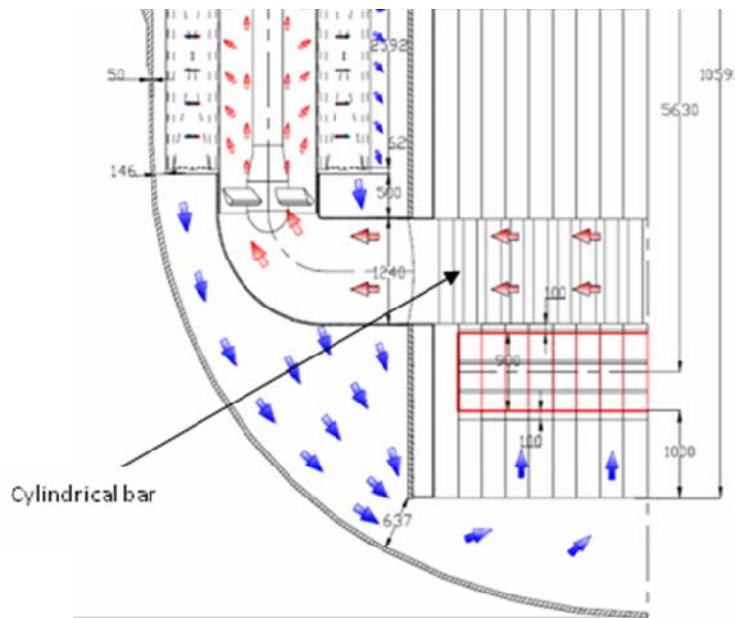
Fig. 6 – Sketch of the lead flow motion in ELSY

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 .
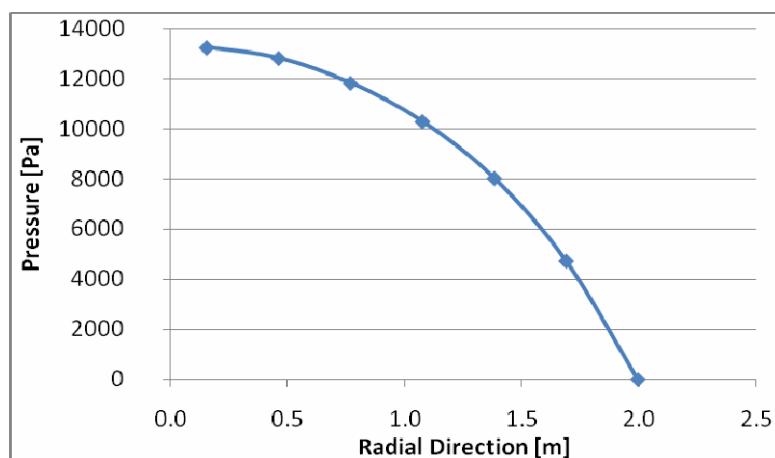
Fig. 7 – Outlet Pressure Drop Distribution

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.
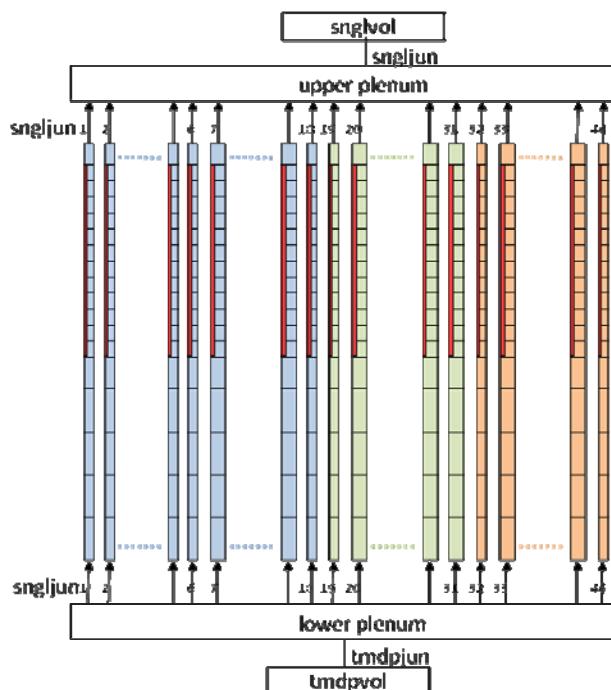
Fig. 8 – Scheme of RELAP5 independent channels model

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 Cooleebrook-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].

$$Nu - 7.55x - 14x^{-6} + 0.007Pe^{0.64+0.246x}$$

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

GEOMETRY			
	FA Grid	21x21	
	# FA	162	
	pin/FA	428	
	FA Side (expanded)	0.2940	m
	Central Hole Side	0.0383	m
	Angular Structures	4	
	Pin Diameter	0.0105	m
	Pin Pitch (expanded)	0.0140	m
	Side Angular Elements	0.0122	m
	P/D Ratio	1.3333	
	FA Flow Area	0.047313	m²
	Hydraulic Diameter	0.013267	m
POWER (BOC)	TOTAL ACTIVE POWER	1.482E+09	W
	INNER POWER	501.4E+6	W
	INTERM POWER	489.2E+6	W
	OUTER POWER	491.6E+6	W
MASSFLOW	Cp	148.77	J/kg/K
	T Inlet	400	°C
	T Outlet	480	°C
	DT	80	°C
	Mass Flowrate	124539	kg/s

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 RELA5 respect the 3D model results underestimated of $130 kg/m^3$ that corresponds to about 1% error in mass flowrate, hence in the ΔT over the core.
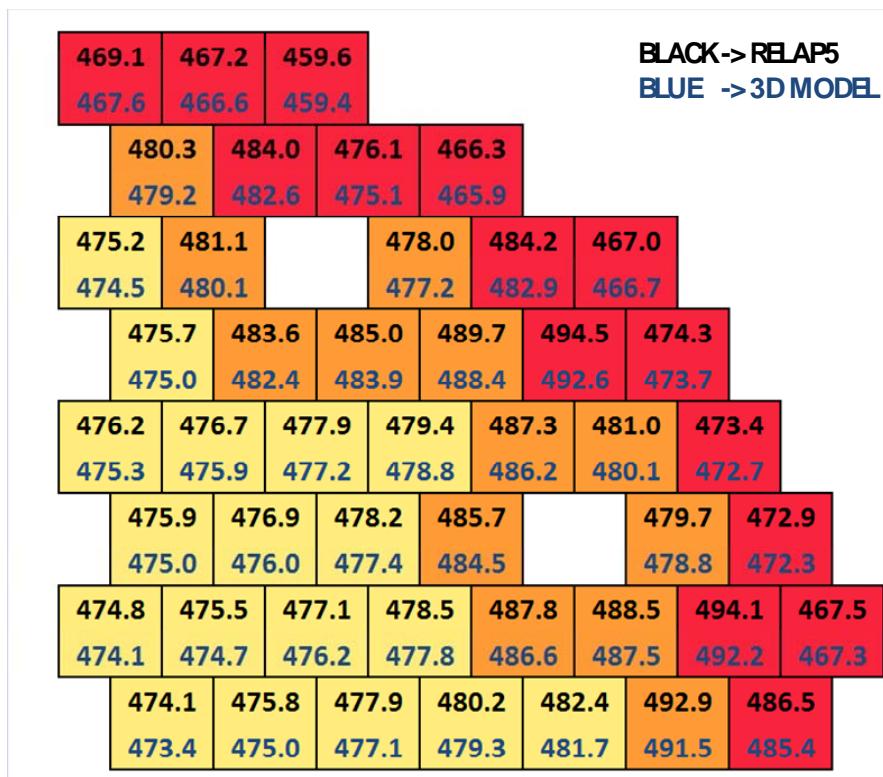
Fig. 9 – Comparison between outlet lead temperatures [°C]

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:

$$T_{clad} = T_{bulk} + \frac{Qr_{pellet}^2}{2hr_{pin}}$$

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.
.
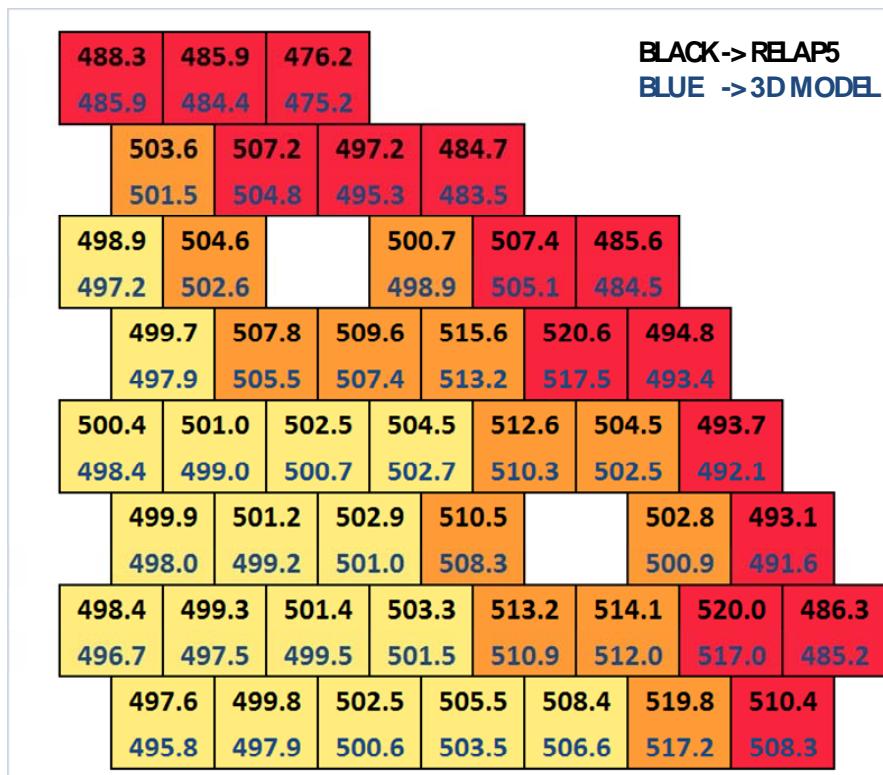
Fig. 10 – Comparison between maximum clad temperatures [°C]

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.
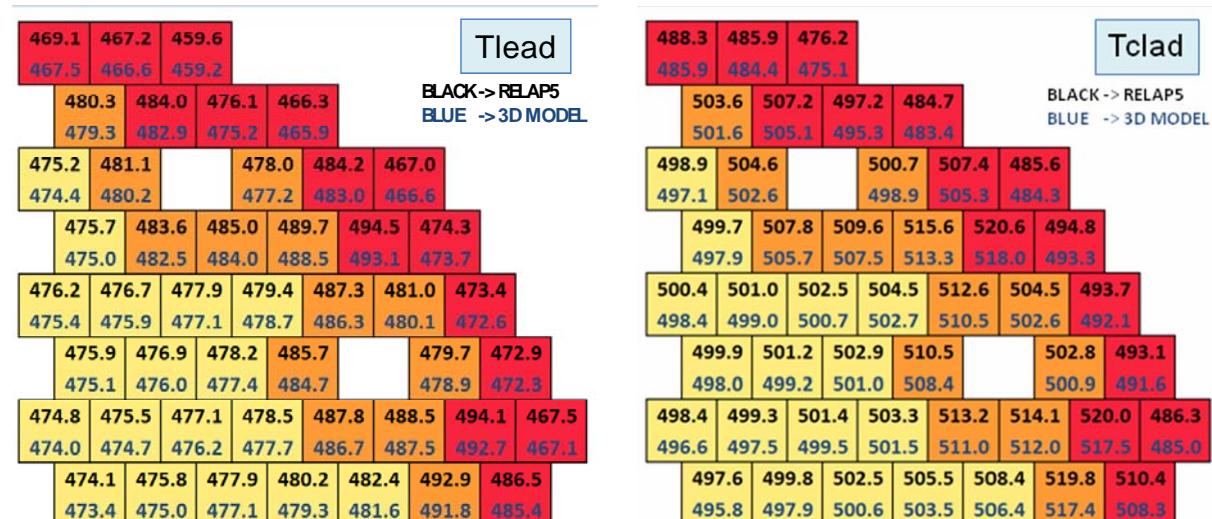
Fig. 11 – Effect of the turbulent viscosity

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.

NO TURBOLENCE   LES TURBOLENT MODEL

a) Tridimensional view of relative temperature

b) Top view of relative temperature
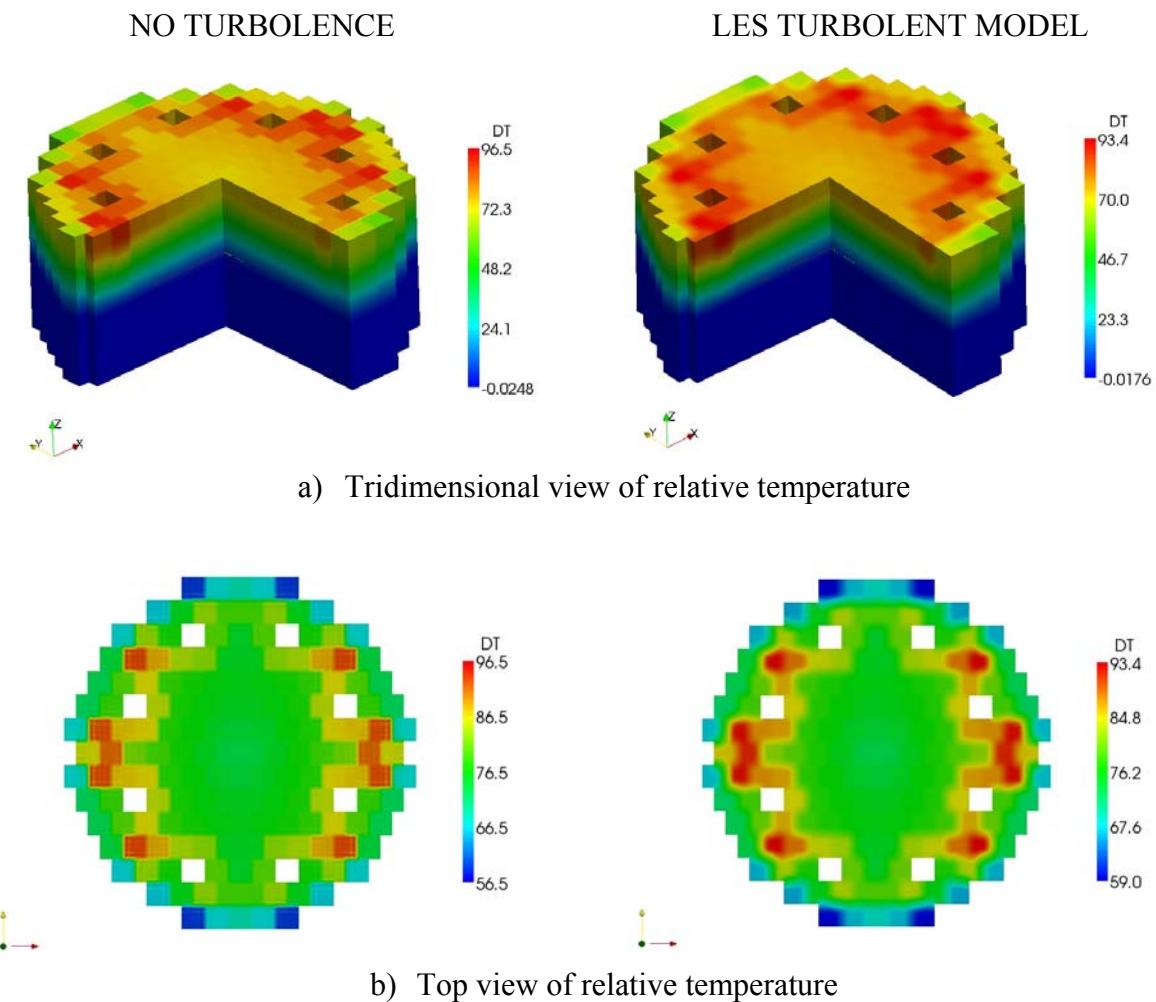
Fig. 12 – Temperature comparison with and without LES turbulence model.

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.
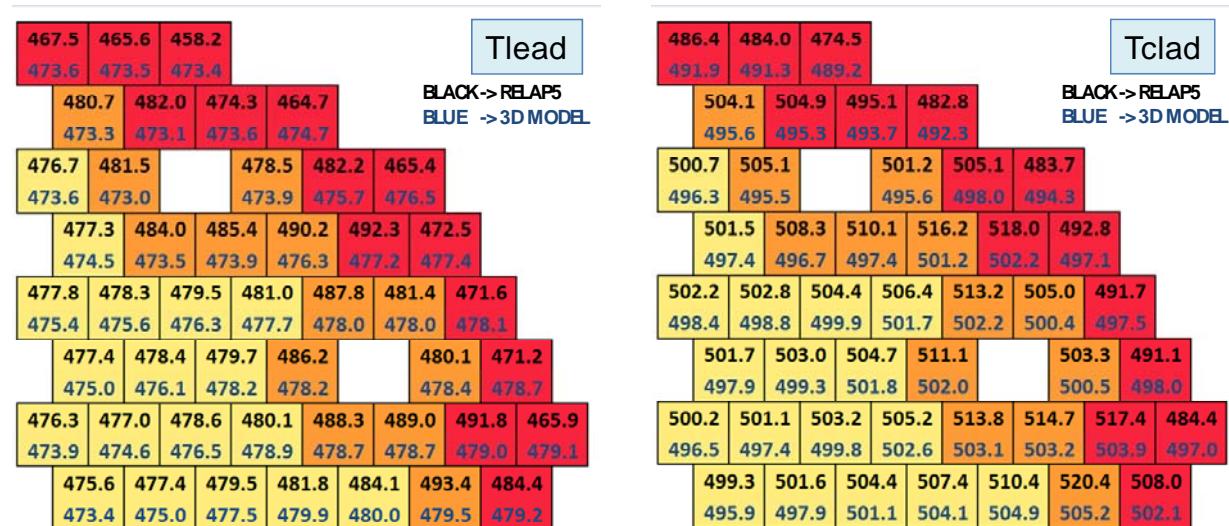
Fig. 13 – Effect of outlet pressure distribution

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 is 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.

a) Relative Temperature

b) Velocity Magnitude

c) Velocity along X axis

d) Velocity along Y axis
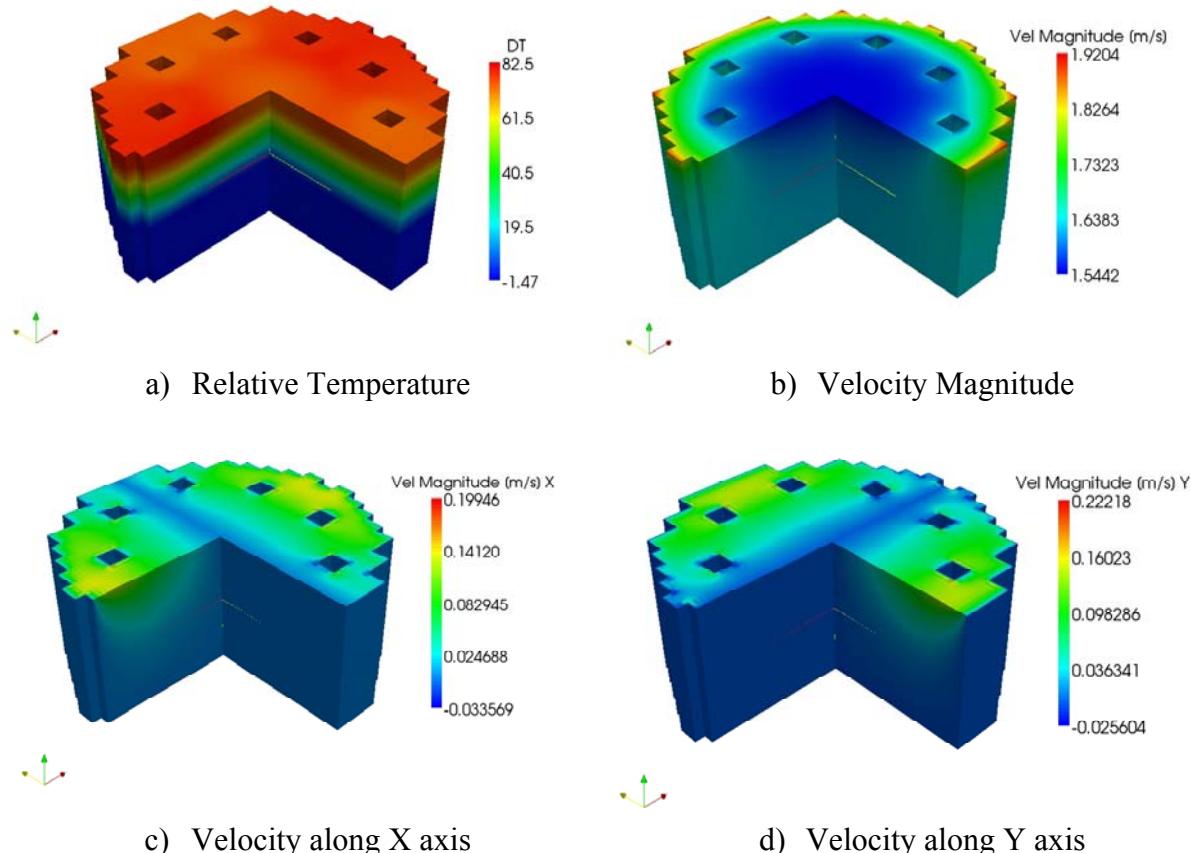
Fig. 14 – Results of the non-uniform pressure outlet calculation

CORE INLET

CORE OUTLET

a) Relative temperature (400°C)

b) Relative temperature (400°C)

c) Velocity

d) Velocity

e) Relative Pressure (bar)

f) Relative Pressure (bar)
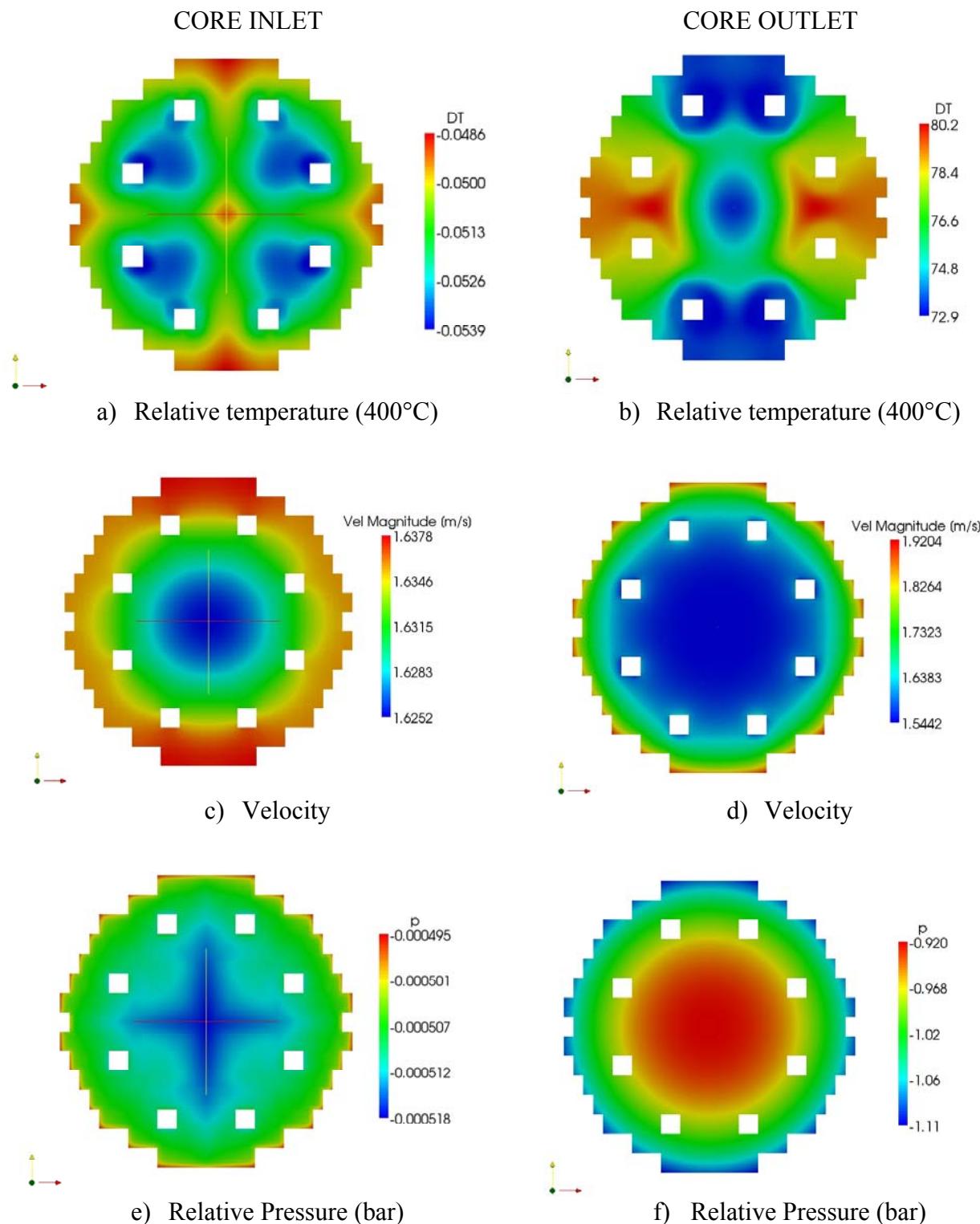
Fig. 15 – Temperature, velocity and pressure at core inlet and outlet

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 sleight 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

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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 MGGauss, defines Gaussian integration;
• the class MGMesh, defines the geometrical mesh;
• the class MGSol, defines the Navier-Stokes equation solver;
• the class MGSolT, 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 "MGSolver.h"
#include "MGSolverT.h"
#include "MGSolverSA.h"
#include "MGSolverCC.h"
```

```
#include "MGMesh.h"
#include "MGGauss.h"
#include "MGCase.h"
#include "config/data.h"
// *******************************************************
// The main program.
// *********************************************************CODE DOCUMENTATION 65
int main(int argc, char** argv) {
#ifdef LIBMESHF
// 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));
printf(" Pe = %e \n",(RHOref*CP0*Lref*Uref)/KAPPA0);
fprintf(stderr," - \n *\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
kfem[0]=3;kfem[1]=9;kfem[2]=27;
// 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," Reading II Gauss:: \n");
MGGauss *dgauss; dgauss=new MGGauss(kng,kfem);CODE DOCUMENTATION 66
dgauss->init(27);// hex27
```

```
MGGauss *dgauss_p; dgauss_p=new MGGauss(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;
#ifdef 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;
#ifdef TURBULENCE
printf("\n Reading Turbulence Operators:: \n");
// Multigrid ------
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;
#ifdef 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;
#ifdef NS_EQUATIONS
fprintf(stderr,"\n NS Initializing:: \n");
fprintf(stderr," Solution: ");
mgs->GenSol(NoLevels-1);
mgs->GenOldSol(NoLevels-1);CODE DOCUMENTATION 67
fprintf(stderr," -\n");
fprintf(stderr," Rhs: ");
fprintf(stderr," -\n");
#endif
#ifdef TURBULENCE
fprintf(stderr,"\n Turbulence Initilize:: ");
fprintf(stderr,"\n Solution: ");
mgsSA->GenSol(*mgmesh1,NoLevels-1);
mgsSA->GenOldSol(NoLevels-1);
fprintf(stderr," - \n");
fprintf(stderr," rhs: ");
mgsSA->GenRhs(*dgauss,*mgmesh1,NoLevels-1);
fprintf(stderr," - \n");
```

```
#endif
#ifdef T_EQUATIONS
printf("\n Energy Initilize:: ");
printf("\n Solution: ");
mgsT->GenSol(NoLevels-1);
mgsT->GenOldSol(NoLevels-1);
printf(" - \n");
#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);
mcase->print_bc(*mgmesh1,*mgs,*mgcc,*mgsT,*mgsSA,t_in,NoLevels-1);
printf(" - \n");
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 << "\n\n*** Solving time step " << t_step+1
<< ", time = " << time+ ND_TIME_STEP << " ***" << std::endl;
// ---------------------------------------------------
Perf_logstart_event("MG Solver");
#ifdef NS_EQUATIONS
// solving V-cyle Multigrid
printf("\n Navier-Stokes solution:: \n");
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 \n" << std::endl;
mgsSA->MGTimeStep(*mgmesh1,*dgauss,0);
#endif
#ifdef T_EQUATIONS
std::cout << std::endl << "\n Energy Solution \n" << 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;
#ifdef LIBMESHF
}
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.

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

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
//#define 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
#ifdef NS_EQUATIONS
#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
#ifdef 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"
#ifdef NS_EQUATIONS
#define FILE_DOFS_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.

command	option	description
#define Uref	1.	Reference velocity
#define Lref	1.	Reference length
#define T_ref	1000.	Reference temperature
#define RHOref	100000.	Reference density
#define T_IN	673.15	Inlet temperature
#define P_IN	36000.	Inlet pressure
#define RHO0	11367.0	density at T^{*1}
#define MU0	.0022	viscosity at T^{*2}
#define KAPPA0	15.8	conductibility at T^{*3}
#define BP0	147.3	conductibility at T^{*4}
#define KOMP0	0.	compressibility at T^{*5}
#define ND_TIME_STEP	0.05	Time step Δt
#define TIME	0.0	Initial time t
#define N_TIME_STEPS	100	Number of time steps
#define QHEAT	1.15e+8	heat volume density source
#define DIRGX	0.	gravity x-direction
#define DIRGY	0.	gravity y-direction
#define DIRGZ	0.	gravity z-direction

Tab. A2 – Parameters available in data.h file

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

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

#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 RHOref 100000.
#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 KAPPA0 15.8
#define PRT 0.9
#define CP0 147.3
#define KOMP0 0.
// 2nd phase
#define RHO1 1.0
#define MU1 0.1
#define KAPPA1 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 accurary 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
```

```
// 3. BPX preconditioned CG = BPXPCGIterId
const IterIdType MLSolverId = MGIterId;
// Nested multigrid iterations? (1. yes 0. no)
const bool NestedMG = 0;
// Type of multigrid: ( 1. V 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 ************************
// Type of restriction operator(1. simple 2. weighted)
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;
// "Smoothing method:" -----------------------------
// 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) = GMRESIte
// 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 = (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
// a.RungeKutta4
// b.explcit
// 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) = GMRESIte
// 9. BiCG = BiCGIter
// 10. QMR = QMRIter
// 11. CGS = CGSIter
// 12. Bi-CGSTAB = BiCGSTABIter
// 13. Test = TestIter
const IterProcType SolvProc = GMRESIter;
//const IterProcType SolvProc = Explicit;
// "pointer to Preconditioner (PrecondProcType) on coarsest grid:"
// Preconditioning: 0. none = (PrecondProcType)NULL
// 1. Jacobi = JacobiPrecond
// 2. SSOR = SSORPrecond
// 3. ILU/ICH = ILUPrecond
const PrecondProcType PrecondProcC = (PrecondProcType)NULL;
//const PrecondProcType PrecondProcC = (PrecondProcType)ILUPrecond;
// ****************************************************
#endif
```

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.

```
/// 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.

```
/// 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 *MGSolver3DNS.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:

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

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 *MGSolver3DT.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 $0 - 1kK$ (mainly for graphical purposes). The user area of the file *MGSolver3DT.C* appear as follow:

```
// ************************
/// 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:
- *MGSolver3DNS.C* for the momentum equations; here are defined $\rho = \rho(T)$ and $\nu = \nu(T)$
- *MGSolver3DT.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 1.1 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.  90.  0.5 4.e-5  0.0  00000
*    cont.  Pres.   Temper.
1200200 3     4.5e5    673.15
*
*
0910000   pbjun1     sngljun
*      from vol.   to vol.   jun. area
0910101    120010000   090010000   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.  90.  1.0 4.e-5  0.0  00000
```

```
1000101 129.21  1.0  0.0  0.  90.  1.0  4.e-5  0.0  00000
*    cont.   Pres.   Temper.
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  vert  delz  rug  hyd  flag
0800101  0.0  1.  1.e6  0.0  90.0  1.0  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
*
1320000   LjunA122    sngljun
1320101  100010000  102000000  0.0  2.1  1.0  00000000
1320201  0.0     0.0     0.0      0.0
*
1330000   LjunA132    sngljun
1330101  100010000  103000000  0.0  2.1  1.0  00000000
1330201  0.0     0.0     0.0      0.0
*
………………
[skip]
………………
*
1470000   LjunA_51    sngljun
1470101  100010000  117000000  0.0  2.1  1.0  00000000
1470201  0.0     0.0     0.0      0.0
*
1480000   LjunA612    sngljun
1480101  100010000  118000000  0.0  2.1  1.0  00000000
1480201  0.0     0.0     0.0      0.0
*
*=======================================================
*=========== UPPER JUNCTIONS INNER ZONE ===========
*=======================================================
*
1610000   UjunA112    sngljun
*    from vol.   to vol.   area  flc  rlc  flag
```

```
1610101    101010000   120000000  0.0   1.9565 0.5   00000000
*        control   flowf    flowg     int.v
1610201    0.0       0.0      0.0       0.0
*
1620000    UjunA122     sngljun
1620101    102010000   120000000  0.0   1.9565 0.5   00000000
1620201    0.0       0.0      0.0       0.0
*
1630000    UjunA132     sngljun
1630101    103010000   120000000  0.0   1.9565 0.5   00000000
1630201    0.0       0.0      0.0       0.0
*
………………..
[skip]
………………..
*
1770000    UjunA_51     sngljun
1770101    117010000   120000000  0.0   1.9565 0.5   00000000
1770201    0.0       0.0      0.0       0.0
*
1780000    UjunA612     sngljun
1780101    118010000   120000000  0.0   1.9565 0.5   00000000
1780201    0.0       0.0      0.0       0.0
*
*====================================================
*=============== PIPES INNER ZONE ================
*====================================================
*
1010000    INN_A112          pipe
1010001    16
1010101    0.023657        16    * flow area
1010301    0.2          4    * volume height
1010302    0.1          5    * volume height
1010303    0.09         15    * volume height
1010304    0.2          16    * volume height *total FA height=1945mm
1010401    0.0          16    * volume of node
1010501    0.0          16    * horizontal angle
1010601    90.0         16    * vertical angle
1010701    0.2          4    * elevation change
1010702    0.1          5    * elevation change
1010703    0.09         15    * elevation change
1010704    0.2          16    * elevation change
1010801    3.0e-6  0.013267   16    * friction factor - roghness
1010901    0.0    0.0       1    * concentrated loss coeff.
1010902    0.0    0.0       2    * concentrated loss coeff.
1010903    0.0    0.0       3    * concentrated loss coeff.
1010904    0.0    0.0       4    * concentrated loss coeff.
1010905    0.0    0.0       5    * concentrated loss coeff.
1010906    0.0    0.0       6    * concentrated loss coeff.
1010907    0.52   0.0       7    * concentrated loss coeff.
1010908    0.0    0.0       8    * concentrated loss coeff.
1010909    0.52   0.0       9    * concentrated loss coeff.
1010910    0.0    0.0       10    * concentrated loss coeff.
1010911    0.52   0.0       11    * concentrated loss coeff.
1010912    0.0    0.0       12    * concentrated loss coeff.
1010913    0.52   0.0       13    * concentrated loss coeff.
1010914    0.0    0.0       14    * concentrated loss coeff.
1010915    0.52   0.0       15    * concentrated loss coeff.
```

```
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.       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 - roghness
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.       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 - roghness
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   LjunA_25    sngljun
2320101   100010000   202000000  0.0  2.1  1.0  00000000
2320201   0.0        0.0      0.0      0.0
*
2330000   LjunA_26    sngljun
2330101   100010000   203000000  0.0  2.1  1.0  00000000
2330201   0.0        0.0      0.0      0.0
*
………………..
[skip]
………………..
*
2420000   LjunA_64    sngljun
2420101   100010000   212000000  0.0  2.1  1.0  00000000
2420201   0.0        0.0      0.0      0.0
*
2430000   LjunA_71    sngljun
2430101   100010000   213000000  0.0  2.1  1.0  00000000
2430201   0.0        0.0      0.0      0.0
*
*===============================================================
*============ UPPER JUNCTIONS INTERMEDIATE ZONE ============
*===============================================================
*
```

```
2610000   UjunA162    sngljun
*       from vol.   to vol.    area  flc  rlc  flag
2610101   201010000  120000000  0.0   1.6938 0.5  00000000
*        control    flowf    flowg    int.v
2610201   0.0       0.0      0.0      0.0
*
2620000   UjunA_25    sngljun
2620101   202010000  120000000  0.0   1.6938 0.5  00000000
2620201   0.0       0.0      0.0      0.0
*
2630000   UjunA_26    sngljun
2630101   203010000  120000000  0.0   1.6938 0.5  00000000
2630201   0.0       0.0      0.0      0.0
*
………………..
[skip]
………………..
*
2720000   UjunA_64    sngljun
2720101   212010000  120000000  0.0   1.6938 0.5  00000000
2720201   0.0       0.0      0.0      0.0
*
2730000   UjunA_71    sngljun
2730101   213010000  120000000  0.0   1.6938 0.5  00000000
2730201   0.0       0.0      0.0      0.0
*
*===========================================================
*================ PIPES INTERMEDIATE ZONE =================
*===========================================================
*
2010000   INT_A162         pipe
2010001   16
2010101   0.023657       16   * flow area
2010301   0.2         4   * volume height
2010302   0.1         5   * volume height
2010303   0.09        15   * volume height
2010304   0.2         16   * volume height *total FA height=1945mm
2010401   0.0         16   * volume of node
2010501   0.0         16   * horizontal angle
2010601   90.0        16   * vertical angle
2010701   0.2         4   * elevation change
2010702   0.1         5   * elevation change
2010703   0.09        15   * elevation change
2010704   0.2         16   * elevation change
2010801   3.0e-6 0.013267   16   * friction factor - roghness
2010901   0.0    0.0     1   * concentrated loss coeff.
2010902   0.0    0.0     2   * concentrated loss coeff.
2010903   0.0    0.0     3   * concentrated loss coeff.
2010904   0.0    0.0     4   * concentrated loss coeff.
2010905   0.0    0.0     5   * concentrated loss coeff.
2010906   0.0    0.0     6   * concentrated loss coeff.
2010907   0.52   0.0     7   * concentrated loss coeff.
2010908   0.0    0.0     8   * concentrated loss coeff.
2010909   0.52   0.0     9   * concentrated loss coeff.
2010910   0.0    0.0     10   * concentrated loss coeff.
2010911   0.52   0.0     11   * concentrated loss coeff.
2010912   0.0    0.0     12   * concentrated loss coeff.
2010913   0.52   0.0     13   * concentrated loss coeff.
```

```
2010914   0.0    0.0        14   * concentrated loss coeff.
2010915   0.52   0.0        15   * concentrated loss coeff.
2011001   0000000         16    * volume flags
2011101   00100000        15    * junction flags
2011201   003  8.00e5  673.16  0.0  0.0  0.0   16
2011300   0
2011301   0.0  0.0  0.      15   *
*
………………..
[skip]
………………..
*
2130000   INT_A_71          pipe
2130001   16
2130101   0.047313        16    * flow area
2130301   0.2            4    * volume height
2130302   0.1            5    * volume height
2130303   0.09           15   * volume height
2130304   0.2            16   * volume height *total FA height=1945mm
2130401   0.0            16   * volume of node
2130501   0.0            16   * horizontal angle
2130601   90.0           16   * vertical angle
2130701   0.2            4    * elevation change
2130702   0.1            5    * elevation change
2130703   0.09           15   * elevation change
2130704   0.2            16   * elevation change
2130801   3.0e-6  0.013267   16    * friction factor - roghness
2130901   0.0    0.0        1    * concentrated loss coeff.
2130902   0.0    0.0        2    * concentrated loss coeff.
2130903   0.0    0.0        3    * concentrated loss coeff.
2130904   0.0    0.0        4    * concentrated loss coeff.
2130905   0.0    0.0        5    * concentrated loss coeff.
2130906   0.0    0.0        6    * concentrated loss coeff.
2130907   0.52   0.0        7    * concentrated loss coeff.
2130908   0.0    0.0        8    * concentrated loss coeff.
2130909   0.52   0.0        9    * concentrated loss coeff.
2130910   0.0    0.0        10   * concentrated loss coeff.
2130911   0.52   0.0        11   * concentrated loss coeff.
2130912   0.0    0.0        12   * concentrated loss coeff.
2130913   0.52   0.0        13   * concentrated loss coeff.
2130914   0.0    0.0        14   * concentrated loss coeff.
2130915   0.52   0.0        15   * concentrated loss coeff.
2131001   0000000         16    * volume flags
2131101   00100000        15    * junction flags
2131201   003  8.00e5  673.16  0.0  0.0  0.0   16
2131300   0
2131301   0.0  0.0  0.      15   *
*
*=====================================================
*============ LOWER JUNCTIONS OUTER ZONE ============
*=====================================================
*
3310000   LjunA172     sngljun
*     from vol.  to vol.  area  flc  rlc  flag
3310101   100010000   301000000   0.0   2.1   1.0   00000000
*     control   flowf    flowg    int.v
3310201   0.0       0.0      0.0      0.0
*
```

```
3320000    LjunA_27     sngljun
3320101    100010000    302000000   0.0  2.1  1.0  00000000
3320201    0.0      0.0      0.0      0.0
*
3330000    LjunA_28     sngljun
3330101    100010000    303000000   0.0  2.1  1.0  00000000
3330201    0.0      0.0      0.0      0.0
*
………………
[skip]
………………
*
3440000    LjunA_82     sngljun
3440101    100010000    314000000   0.0  2.1  1.0  00000000
3440201    0.0      0.0      0.0      0.0
*
3450000    LjunA_83     sngljun
3450101    100010000    315000000   0.0  2.1  1.0  00000000
3450201    0.0      0.0      0.0      0.0
*
*=======================================================
*============ UPPER JUNCTIONS OUTER ZONE ============
*=======================================================
*
3610000    UjunA172     sngljun
*      from vol.   to vol.    area flc  rlc  flag
3610101    301010000    120000000   0.0  1.1791 0.5  00000000
*      control    flowf     flowg     int.v
3610201    0.0      0.0      0.0      0.0
*
3620000    UjunA_27     sngljun
3620101    302010000    120000000   0.0  1.1791 0.5  00000000
3620201    0.0      0.0      0.0      0.0
*
3630000    UjunA_28     sngljun
3630101    303010000    120000000   0.0  1.1791 0.5  00000000
3630201    0.0      0.0      0.0      0.0
*
………………
[skip]
………………
*
3740000    UjunA_82     sngljun
3740101    314010000    120000000   0.0  1.1791 0.5  00000000
3740201    0.0      0.0      0.0      0.0
*
3750000    UjunA_83     sngljun
3750101    315010000    120000000   0.0  1.1791 0.5  00000000
3750201    0.0      0.0      0.0      0.0
*
*=======================================================
*=============== PIPES OUTER ZONE ================
*=======================================================
*
3010000    OUT_A172         pipe
3010001    16
3010101    0.023657        16  * flow area
3010301    0.2         4  * volume height
```

```
3010302   0.1            5    * volume height
3010303   0.09          15    * volume height
3010304   0.2           16    * volume height *total FA height=1945mm
3010401   0.0           16    * volume of node
3010501   0.0           16    * horizontal angle
3010601   90.0          16    * vertical angle
3010701   0.2            4    * elevation change
3010702   0.1            5    * elevation change
3010703   0.09          15    * elevation change
3010704   0.2           16    * elevation change
3010801   3.0e-6 0.013267    16    * friction factor - roghness
3010901   0.0    0.0     1    * concentrated loss coeff.
3010902   0.0    0.0     2    * concentrated loss coeff.
3010903   0.0    0.0     3    * concentrated loss coeff.
3010904   0.0    0.0     4    * concentrated loss coeff.
3010905   0.0    0.0     5    * concentrated loss coeff.
3010906   0.0    0.0     6    * concentrated loss coeff.
3010907   0.52   0.0     7    * concentrated loss coeff.
3010908   0.0    0.0     8    * concentrated loss coeff.
3010909   0.52   0.0     9    * concentrated loss coeff.
3010910   0.0    0.0    10    * concentrated loss coeff.
3010911   0.52   0.0    11    * concentrated loss coeff.
3010912   0.0    0.0    12    * concentrated loss coeff.
3010913   0.52   0.0    13    * concentrated loss coeff.
3010914   0.0    0.0    14    * concentrated loss coeff.
3010915   0.52   0.0    15    * concentrated loss coeff.
3011001   0000000       16    * volume flags
3011101   00100000      15    * junction flags
3011201   003 8.00e5 673.16 0.0 0.0 0.0   16
3011300   0
3011301   0.0 0.0 0.     15    *
*
………………..
[skip]
………………..
*
3150000   OUT_A_83            pipe
3150001   16
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 - roghness
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.
```

```
3150908   0.0   0.0         8   * concentrated loss coeff.
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 ============================*
*
11011000  10 19 2 1 0.0 0  1 32
11011100  0 1
11011101  12 4.5e-3  3 4.65e-3  3 5.25e-3
11011201  1   12
11011202  2   15
11011203  3   18
11011301  1.  12
11011302  0.  18
11011400  0
11011401  673.16  19
11011501  0          0      0 1 19.26  10
11011601  101060000     10000  110 1 19.26  10
11011701  101  8.60089e-02  0.0  0.0  1
11011702  101  9.32998e-02  0.0  0.0  2
11011703  101  1.03749e-01  0.0  0.0  3
11011704  101  1.10010e-01  0.0  0.0  4
11011705  101  1.14410e-01  0.0  0.0  5
11011706  101  1.13892e-01  0.0  0.0  6
11011707  101  1.09049e-01  0.0  0.0  7
11011708  101  1.01844e-01  0.0  0.0  8
11011709  101  9.05869e-02  0.0  0.0  9
11011710  101  7.71503e-02  0.0  0.0  10
11011900  1
11011901  0.013267 100. 100. 0. 0. 0. 0. 1. 1. 1.3333 1. 10
*
11021000  10 19 2 1 0.0 0  1 32
11021100  0 1
11021101  12 4.5e-3  3 4.65e-3  3 5.25e-3
11021201  1   12
11021202  2   15
11021203  3   18
11021301  1.  12
11021302  0.  18
11021400  0
11021401  673.16  19
11021501  0          0      0 1 19.26  10
11021601  102060000     10000  110 1 19.26  10
11021701  102  8.60089e-02  0.0  0.0  1
11021702  102  9.32998e-02  0.0  0.0  2
11021703  102  1.03749e-01  0.0  0.0  3
```

```
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
*
………………..
[skip]
………………..
*
11181000  10 19 2 1 0.0 0  1 32
11181100  0 1
11181101  12 4.5e-3  3 4.65e-3  3 5.25e-3
11181201  1  12
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     10000  110 1 19.26  10
11181701  118  8.60089e-02  0.0  0.0  1
11181702  118  9.32998e-02  0.0  0.0  2
11181703  118  1.03749e-01  0.0  0.0  3
11181704  118  1.10010e-01  0.0  0.0  4
11181705  118  1.14410e-01  0.0  0.0  5
11181706  118  1.13892e-01  0.0  0.0  6
11181707  118  1.09049e-01  0.0  0.0  7
11181708  118  1.01844e-01  0.0  0.0  8
11181709  118  9.05869e-02  0.0  0.0  9
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
*
*================================================================*
*==================== HEAT STRUCTURE CORE ====================*
*==================== INTERMEDIATE ZONE ==========================*
*
12011000  10 19 2 1 0.0 0  1 32
12011100  0 1
12011101  12 4.5e-3  3 4.65e-3  3 5.25e-3
12011201  1  12
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     10000  110 1 19.26  10
12011701  201  8.48697e-02  0.0  0.0  1
12011702  201  9.63034e-02  0.0  0.0  2
12011703  201  1.06399e-01  0.0  0.0  3
```

```
12011704  201  1.12959e-01  0.0  0.0  4
12011705  201  1.16319e-01  0.0  0.0  5
12011706  201  1.15623e-01  0.0  0.0  6
12011707  201  1.10313e-01  0.0  0.0  7
12011708  201  1.00872e-01  0.0  0.0  8
12011709  201  8.55509e-02  0.0  0.0  9
12011710  201  7.07905e-02  0.0  0.0  10
12011900  1
12011901  0.013267  100. 100.  0. 0. 0. 0.  1. 1.  1.3333  1. 10
*
………………..
[skip]
………………..
*
12131000  10 19 2 1 0.0 0  1 32
12131100  0 1
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
12131703  213  1.06399e-01  0.0  0.0  3
12131704  213  1.12959e-01  0.0  0.0  4
12131705  213  1.16319e-01  0.0  0.0  5
12131706  213  1.15623e-01  0.0  0.0  6
12131707  213  1.10313e-01  0.0  0.0  7
12131708  213  1.00872e-01  0.0  0.0  8
12131709  213  8.55509e-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
*
*================================================================*
*==================== HEAT STRUCTURE CORE ====================*
*======================= OUTER ZONE =============================*
*
13011000  10 19 2 1 0.0 0  1 32
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
13011701  301  8.33685e-02  0.0  0.0  1
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
13011710  301  6.75547e-02  0.0  0.0  10
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
13151101  12 4.5e-3  3 4.65e-3  3 5.25e-3
13151201  1  12
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  0.01326 100. 100. 0. 0. 0. 0.  1. 1.  1.3333  1. 10
*
*=================================================================
*=================================================================
************* POWER TABLES INNER ZONE *******************
*=================================================================
*** FA 1-1/2
*
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
*
20210200     power    402  1. 4400533.2
20210201    -1.0     0.0
20210202     0.0     0.0
20210203     20.0    1.0 *100%
```

```
20210204   3000.0    1.0
*
*** FA 1-3/2
*
20210300    power    402   1. 4521336.8
20210301    -1.0     0.0
20210302     0.0     0.0
20210303    20.0     1.0 *100%
20210304   3000.0    1.0
*
………………..
[skip]
………………..
*
*** FA 6-1/2
*
20211800    power    402   1. 4362611.1
20211801    -1.0     0.0
20211802     0.0     0.0
20211803    20.0     1.0 *100%
20211804   3000.0    1.0
*
*=================================================================
********** POWER TABLES INTERMEDIATE ZONE ***************
*=================================================================
*** FA 1-6/2
*
20220100    power    402   1. 5387682.0
20220101    -1.0     0.0
20220102     0.0     0.0
20220103    20.0     1.0 *100%
20220104   3000.0    1.0
*
*** FA 2-5
*
20220200    power    402   1. 10188157.0
20220201    -1.0     0.0
20220202     0.0     0.0
20220203    20.0     1.0 *100%
20220204   3000.0    1.0
*
………………..
[skip]
………………..
*
*** FA 6-4
*
20221200    power    402   1. 9056747.7
20221201    -1.0     0.0
20221202     0.0     0.0
20221203    20.0     1.0 *100%
20221204   3000.0    1.0
*
*** FA 7-1
*
20221300    power    402   1. 9317902.3
20221301    -1.0     0.0
20221302     0.0     0.0
```

```
20221303    20.0    1.0 *100%
20221304    3000.0    1.0
*
*================================================================
************* POWER TABLES OUTER ZONE *******************
*================================================================
*
*** FA 1-7/2
*
20230100    power    402    1. 5018234.2
20230101    -1.0    0.0
20230102     0.0    0.0
20230103    20.0    1.0 *100%
20230104    3000.0    1.0
*
*** FA 2-7
*
20230200    power    402    1. 10908286.9
20230201    -1.0    0.0
20230202     0.0    0.0
20230203    20.0    1.0 *100%
20230204    3000.0    1.0
*
………………..
[skip]
………………..
*
* *** FA 8-2
*
20231400    power    402    1. 7806020.5
20231401    -1.0    0.0
20231402     0.0    0.0
20231403    20.0    1.0 *100%
20231404    3000.0    1.0
*
* *** FA 8-3
*
20231500    power    402    1. 6922160.7
20231501    -1.0    0.0
20231502     0.0    0.0
20231503    20.0    1.0 *100%
20231504    3000.0    1.0
*
*-----------------------------------------------------------------
* CONTROL VARIABLeS
*-----------------------------------------------------------------
*
*************************************************
*  Delta T core
20500100  delTCR sum 1. 0.0 1
20500101  0.0  1. tempf 120010000
20500102    -1. tempf 100010000
*
* Total DP CORe *
*
20500200  Deltapc   sum   1.0   0.0 1
20500201  0.0   1.0   p  100010000
20500202        -1.0   p  120010000
```

```
*
* Static DP CORe *
*
20500300   rhogAVGc   sum   9.81  306705. 1
20500301   0.0   0.2   rhof   101010000
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   30271.75 1
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
20100122 1423. 2.76
20100123 1473. 2.69
20100124 1523. 2.64
20100125 1573. 2.59
20100126 1623. 2.54
20100127 1673. 2.50
20100128 1723. 2.47
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 2773. 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
```

```
20100305  450. 26.30
20100306  500. 26.86
20100307  550. 27.35
20100308  600. 27.78
20100309  650. 28.13
20100310  700. 28.40
20100311  750. 28.61
20100312  800. 28.74
20100313  850. 28.80
20100314  900. 28.78
20100315  950. 28.70
20100316 1000. 28.54
20100317 3000. 28.54
*
*    "     heat capacity (j/m3/k)
* from Sobolev doc. for T91
20100351   3. 3.44e6
20100352  300. 3.44e6
20100353  350. 3.69e6
20100354  400. 3.82e6
20100355  450. 3.94e6
20100356  500. 4.04e6
20100357  550. 4.15e6
20100358  600. 4.29e6
20100360  650. 4.47e6
20100361  700. 4.70e6
20100362  750. 4.98e6
20100363  800. 5.31e6
20100364  850. 5.69e6
20100365  900. 6.11e6
20100366  950. 6.54e6
20100367 1000. 6.99e6
20100368 3000. 6.99e6
*
.
```