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Water Reactors

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COOLANT MIXING IN PRESSURIZED WATER REACTORS

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ABSTRACT

For the analysis of boron dilution transients and main steam line break scenarios the modelling of the coolant mixing inside the reactor vessel is important. The reactivity insertion due to overcooling or deboration depends strongly on the coolant temperature and boron concentration.

The three-dimensional flow distribution in the downcomer and the lower plenum of PWR's was calculated with a computational fluid dynamics (CFD) code (CFX-4). Calculations were performed for the PWR's of SIEMENS KWU, Westinghouse and VVER-440 / V-230 type. The following important factors were identified: exact representation of the cold leg inlet region (bend radii etc.), extension of the downcomer below the inlet region at the PWR Konvoi, obstruction of the flow by the outlet nozzles penetrating the downcomer, etc. The k-ε turbulence model was used. Construction elements like perforated plates in the lower plenum have large influence on the velocity field. It is impossible to model all the orifices in the perforated plates. A porous region model was used to simulate perforated plates and the core. The porous medium is added with additional body forces to simulate the pressure drop through perforated plates in the VVER-440. For the PWR Konvoi the whole core was modelled with porous media parameters. The velocity fields of the PWR Konvoi calculated for the case of operation of all four main circulation pumps show a good agreement with experimental results. The CFD-calculation especially confirms the back flow areas below the inlet nozzles. The downcomer flow of the Russian VVER-440 has no recirculation areas under normal operation conditions. By CFD calculations for the downcomer and the lower plenum an analytical mixing model used in the reactor dynamic code DYN3D was verified. The measurements, the analytical model and the CFD-calculations provided very well agreeing results particularly for the inlet region.

The difficulties of analytical solutions and the uncertainties of turbulence models for the numerical solutions require additional experiments. Therefore a 1:5 scaled plexiglas model is under construction at RC Rossendorf. The model can be used variably for PWR's of KONVOI- and EPR- types including the primary loops. The measurements of the mixing effects will be performed with modern wire mesh sensors based on conductivity differences and LDA is used to measure the flow conditions.

1. INTRODUCTION

Efficient models for the description of temperature and boron concentration distribution at the core inlet have to be developed for the case of different conditions in the cold legs of the primary circuit. The emphasis is put on ATWS accidents, boron dilution accidents and steam line breaks. Further, the mixing between core outlet and reactor outlet nozzles has to be described. The main goal is to provide computationally efficient modules for the coupling of thermal hydraulic computer codes with three-dimensional neutron-kinetic models.

Starting from existing analytical solutions for the velocity and temperature fields in VVER reactors similar models will be developed and checked with regard to their feasibility for Western PWRs. The specific geometrical boundary conditions have to be taken into account, because they lead to considerable differences in the velocity profile.

Another aim is to validate the CFD-Code and the existing analytical solutions for the velocity and temperature fields under steady state conditions (nominal flow) against measurements and to compare the flow field and the coolant mixing in the Russian VVER-440 type reactors with the German type reactor SIEMENS Konvoi.

2. GEOMETRY AND TECHNICAL DATA OF THE PWR KONVOI AND THE VVER-440

The Primary Cuircit of the PWR Konvoi has 4 loops, the inlet and outlet nozzles are in the same plane.

The VVER-440 has 6 loops and the outlet nozzles are above the inlet nozzles. In the paper presented, only the V-230 design version of VVER-440 is considered, which has a perforated plate at the inlet of the lower control rod chamber, but no elliptical sieve for additional flow smoothing like the V-213.

Tab. 1: Comparison of the Reactor Types PWR Konvoi and VVER-440

Reactor types	PWR KONVOI (1300 MW$_{el}$)	VVER-440 (440 MW$_{el}$)
No of Loops	4	6
Mass flow per loop/ kg/s	18800	8550
inlet temperature / °C	291.3	268.8
pressure / bar	158	125
velocity at the inlet nozzles / m/s	14.2	9.55

3. THE ANALYTICAL MIXING MODEL

A special model for the mixing of coolant from different primary loops in the downcomer and lower plenum of VVER-440 type reactors was introduced by Dräger /4/. This model is based on the analytical solution of the Navier-Stokes equations in the potential flow approximation for a 2D flow in the downcomer. The velocity gradient in the radial direction was neglected. In the lower control rod chamber a parallel flow with constant velocity was assumed.

The flow field in the lower plenum, where the coolant changes its flow direction is controlled by a downcomer outlet boundary condition, i.e. there is no modelling of the flow field in this part. With this approximation of the velocity field the diffusion equation for the temperature is solved. The solution is presented as a closed analytical expression based on series of orthogonal eigen-functions. The turbulence was taken into account by constant scalar turbulent thermal conductivities defined individually for the downcomer and the lower control rod chamber. The turbulent Peclet numbers describe the intensity of turbulent diffusion. Dräger has found that in the case of highly turbulent flow the mixing can be well described by choosing values for these two Pe-numbers on the basis of experimental data. These values are able to generalize the mixing behaviour, i.e. they are insensitive against changes of the operation mode of the reactor (e.g. different situations of disturbed reactor inlet temperatures, mass flow rates of running pumps etc.) in the case of operating MCP's in a VVER-440.

However, the assumption of the absence of vortices in the downcomer is not fulfilled in general. Further, the model was not yet tested for natural circulation conditions.

The analytical model is used in the reactor dynamics code DYN3D /6/ to describe the coolant mixing in VVER-440 type reactors. In the coupled code complex DYN3D-ATHLET it links the cold leg parameters with the reactor core inlet distributions. This code system was used for the analysis of main steam line break scenarios for VVER-440 type reactors.

In order to validate the analytical mixing model, measured values from an air operated 1:5 scaled VVER-440 model were used /3, 4, 5/. The use of air for liquid flows has the advantage to have sufficiently large Reynolds numbers and to be technologically better controllable. Temperature measurement technology was used and the measurements were performed at the end of the downcomer and at the inlet of the reactor core.

Measurement results from the air flow model were used to validate the CFD-calculations, too.

4. ASSUMPTIONS FOR CFD-CALCULATIONS

4.1 View of the software package CFX 4.2

CFX is a finite volumes program /1/ that offers the following options

- Block structured discretization grids

- Solution of the Navier-Stokes-Equations for steady and unsteady flows for compressible and not compressible fluids

- Applicability for laminary and turbulent flows (different models of turbulence) and non Newtonian fluids

- Modelling of heat transfers

- Use of different coordinate systems

4.2 Model assumptions, geometry preparation and grid generation
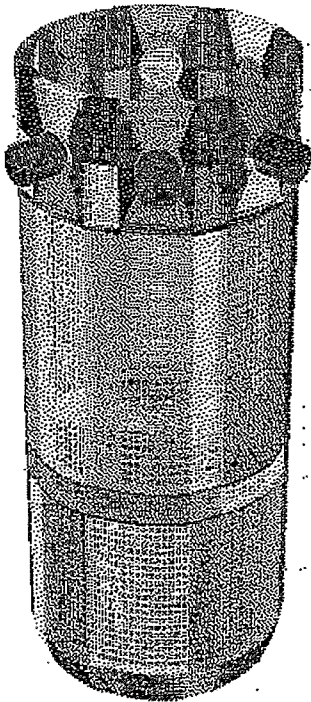
Following assumptions for the modeling of the coolant flow in pressurized water reactors are made:

- incompressible fluid
- use of the Standard k-ε turbulence model
- pressure boundary condition at the outlet
- applying passive scalar fields to describe boron concentration
- simulation of perforated plates with the help of a porous medium
- simulation of the pressure resistance to sieve plates with the help of Body Forces
- model the heat transfer

For the CFD calculations a SGI Origin 200 workstation (1 GB RAM, 4x R 10000 processors of 180 MHz,64 Bit CPU) was used.

Fig. 1 Grid model the VVER-440

For the calculations following discretizations (Tab. 2) have been developed (see Fig. 1):

Tab. 2: Discretizations of the Reactor Types PWR Konvoi and VVER-440

| PWR	No. of Blocks	No. of Patches	No. of Grid cells
KONVOI	166	685	109194
VVER-440	236	912	159800

In order to receive an optimal net griding for the later flow simulation one must consider the following items: Checking grid number in special regions to minimize numerical diffusion, refinement of the griding in fields with strong changes of the dependent variables, adaptation of the griding to estimated flow lines, generation of nets as orthogonal as possible (angle >20°).

4.3 Boundary conditions and the modeling of the perforated plate (VVER-440) and the core (Konvoi)

At both reactor types the inlet boundary conditions were set at the inlet nozzles. The outlet boundary conditions were set to pressure controlled. In the case of the VVER-440 / V-230 there was no need to model the reactor core because the outlet boundary conditions are dominated by the control rod chamber (Fig.2). The core was modeled at the PWR Konvoi because the lower plenum boundary conditions are more strongly influenced by the core .

In the case of the reactor model VVER-440 / V-230, no elliptical sieve plate exists. However, a perforated plate is located at the inlet into the lower control rod chamber below the core inlet. This plate plays a important role for controlling the size and the place of the vortices and therefore for mixing the coolant.
It was also not possible to simulate the whole core with the fuel elements, control elements etc. The flow volume has a certain degree of porosity γ , which can be chosen anisotropically. Further, within a porous medium, body forces can be defined to describe distributed friction losses.
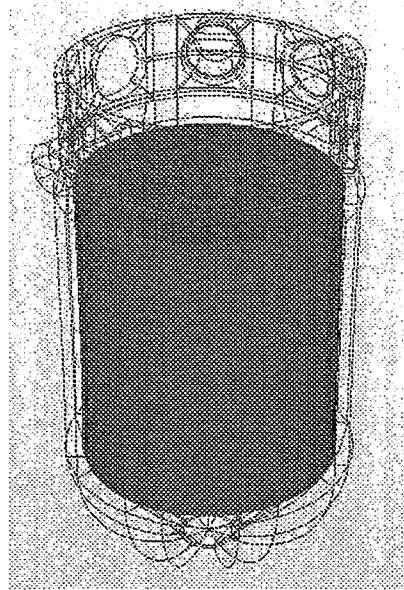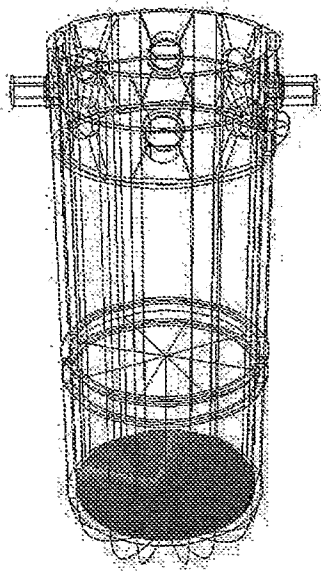
The porosity value γ for perforated plates can be determined easily, by relating the area of orifices to the total area of the sieve plate . The body forces B are added to the momentum equation. The porosity value γ describes the change of free flow area A within the porous medium.

Fig. 2 Perforated plate (VVER-440) and core (Konvoi) as a porous media

The momentum equation:

$$\frac{\partial \rho u_i}{\partial t} + \nabla\left(\rho u_i \otimes u_i\right) = B + \nabla\sigma \qquad i=1,2,3 \qquad (1)$$

$$B = B_F - \left(R_C + R_F|v|\right)v \qquad (2)$$

The speed-factor R_F .(kg/m^4) is useful to calculate a flow resistance depending on the local velocity. The following relation between the Speed-Factor R_F and the flow resistance coefficient ζ is valid:

$$R_F = \zeta \frac{A}{V}\frac{\rho}{2} \qquad (3)$$

Measured values for the flow resistance ζ were used to calculate the speed-factor R_F at the perforated plate of the VVER-440. For the Konvoi core calculated values from SIEMENS KWU were taken to simulate the flow resistance ζ.

5. RESULTS

5.1 Steady flow results in the PWR Konvoi

The calculated velocity field of the PWR Konvoi agrees well with experimental results (air operated model of Ulrych and Weber /2/). This especially confirms the back flow areas below the inlet nozzles. The coolant mixing at nominal condition is low (App /Fig. 1). A sector of low temperature coolant is existing at the inlet of the core if in one of the loops lower temperature is assumed. A maximum velocity exists at azimutal positions between the inlet and outlet nozzles.

5.2 Flow field in the VVER-440

The downcomer flow of the Russian VVER-440 has no back flow areas. With calculations of the downcomer and lower plenum there could be confirmed the validity of the analytical mixing model of Dräger /4/ (applicability of potential flow approximation). In the case of VVER-440, no recirculation vortices are found. However, a maximum velocity exists also on azimutal positions between the inlet nozzles. In Fig. 3 the velocity at azimutal positions at the end of the downcomer at the VVER-440 is shown.
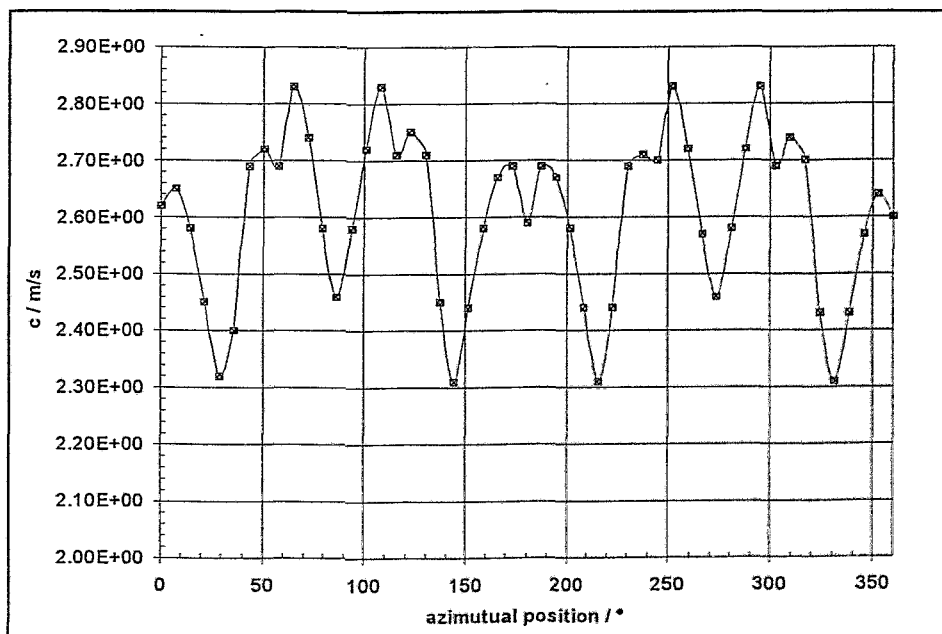

Fig. 3 Velocity distribution at the end of the downcomer of VVER-440

The flow fields in the downcomer, nozzle plane and lower plenum of the VVER-440 / V-230 are represented in App./Fig 2/3 at steady state conditions. In App./Fig. 4, the flow field of the

DWR Konvoi was added to compare it with the flow field of the VVER-440. The flow field is more homogenous than at PWR Konvoi. However, in the lower plenum of the VVER-440 large vortices are existing. The perforated plate is controlling the size and location of the vortices and therefore also the mixing of the coolant. The maximum velocity at the core inlet is situated at the outer core radius (App./Fig.2).

5.3 Comparison of the mixing phenomena with measurements and the analytical model at the VVER-440
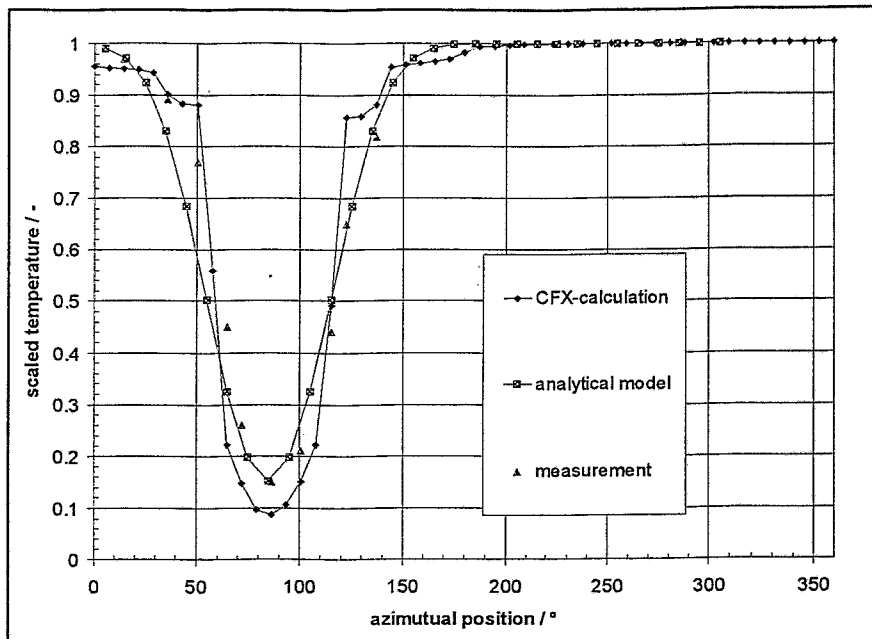

Fig. 4 Scaled temperature distribution at the end of the downcomer of VVER-440

In Fig. 4 the temperature distribution at the downcomer outlet is shown, when all loops are in operation. One of the six loops is operating with lower temperature. This case was also investigated in the air operated mixing model of the VVER-440. Incomplete mixing occurs i.e. a sector of cold water is located below the inlet nozzle. There is almost no mixing in the downcomer flow field that means a relatively sharp sector of cold water is located below the inlet nozzle (App. /Fig.3) .

The comparison of the 2 planes close to the perforated plate and below the core inlet indicates a good mixing in the lower control rod chamber (App. /Fig.3). In the left picture App./Fig.3 there is a field of low temperature recognizable, that appears below the reactor core with less intensity.

Fig. 5 shows the scaled temperature distribution over the core diameter of the VVER-440/V-230. A comparison between CFD-calculation, measurement and analytical model shows a good agreement .The CFD-calculation shows the lowest mixing rate, which can be seen from the greater difference between maximum and minimum scaled temperatures. This could be a result of the turbulence model in the CFD-calculation (k, ε - Model). However, sector formation can be clearly seen in all processes.
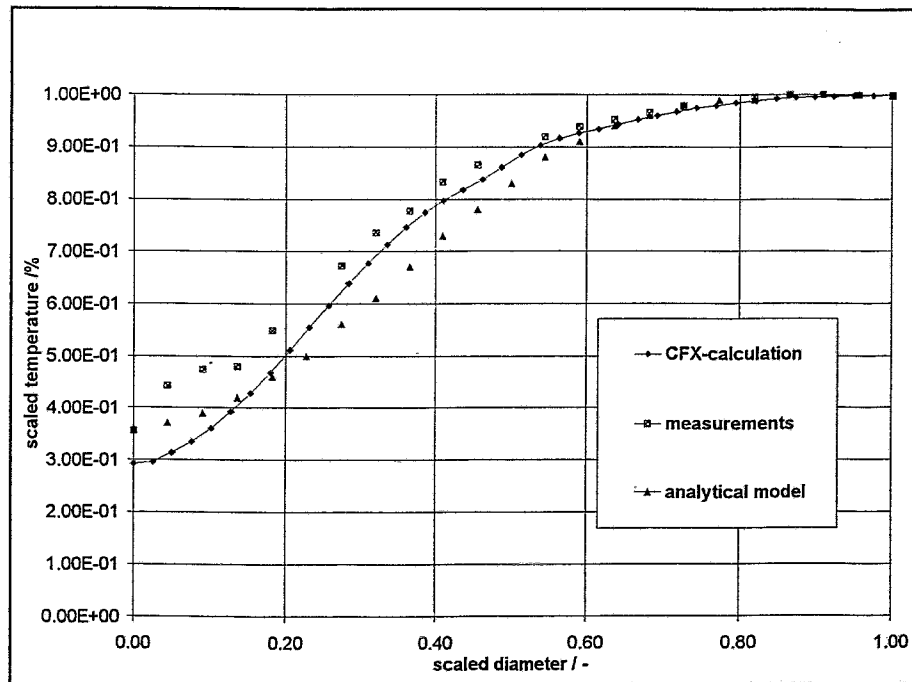

Fig. 5 Scaled temperature distribution at the core inlet of the VVER-440

6. COOLANT MIXING TEST FACILITY AT RCR

The validation of the theoretical models, especially with respect to the choice of an appropriate turbulence model or the dispersion coefficients in the analytical solutions respectively, requires experiments at a test facility, which is reproducing the flow phenomena of the original reactor as much as possible. For KONVOI type reactors such a test facility did not exist up to now. To find an optimum scaling factor for the flow model, CFD-calculations were performed. It turned out that the 1:5 scaling meets economic and physical demands optimally. The flow fields are shown to be self similar for this scaling factor.

The requirements concerning quality of the experimental results need a non- pressurized test rig operated with water (room temperature). It has to dispose of separately controllable main coolant pumps in each loop (Fig. 6). The measurement instrumentation has to be designed for

the required spatial and time resolution. This test facility was constructed at the Research Center Rossendorf and test operations have already been performed.
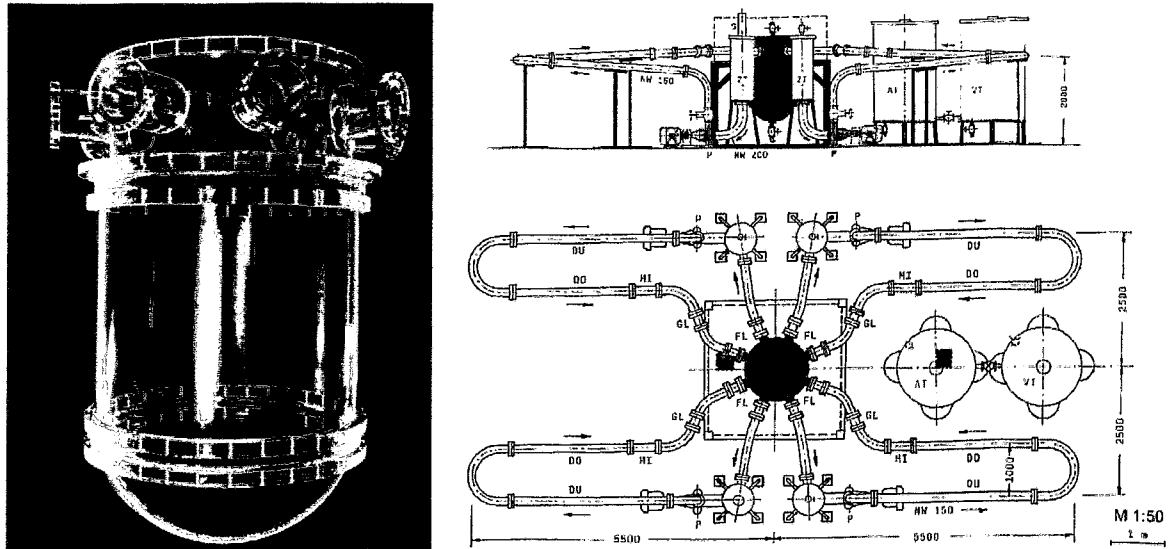

Fig. 6 1:5 scaled plexiglas model of the PWR Konvoi

7. LITERATURE

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8. NOMENCLATURE

u_i component of velocity in m/s

x_i position coordinate in m

ρ density in $\dfrac{kg}{m^3}$

p static pressure in Pa

t time

η viscosity

T temperature in K

k turbulent kinetic energy

ε dissipation factor

γ volume porosity

B Body Force $\dfrac{N}{m^3}$

B_F Body Force $\dfrac{N}{m^3}$

R_C resistance factor $\dfrac{kg}{m^3}$

R_F velocity factor $\dfrac{kg}{m^4}$

A surface m^2

V volume m^3

ζ flow resistance

σ shear stress

9. APPENDIX

(1)

(2)

(3)

(4)

c [m/s]

2.3132E+01
1.9277E+01
1.5421E+01
1.1566E+01
7.7106E+00
3.8553E+00
0.0000E+00

T [K]

5.6440E+02
5.2383E+02
4.8327E+02
4.4270E+02
4.0213E+02
3.6157E+02
3.2100E+02
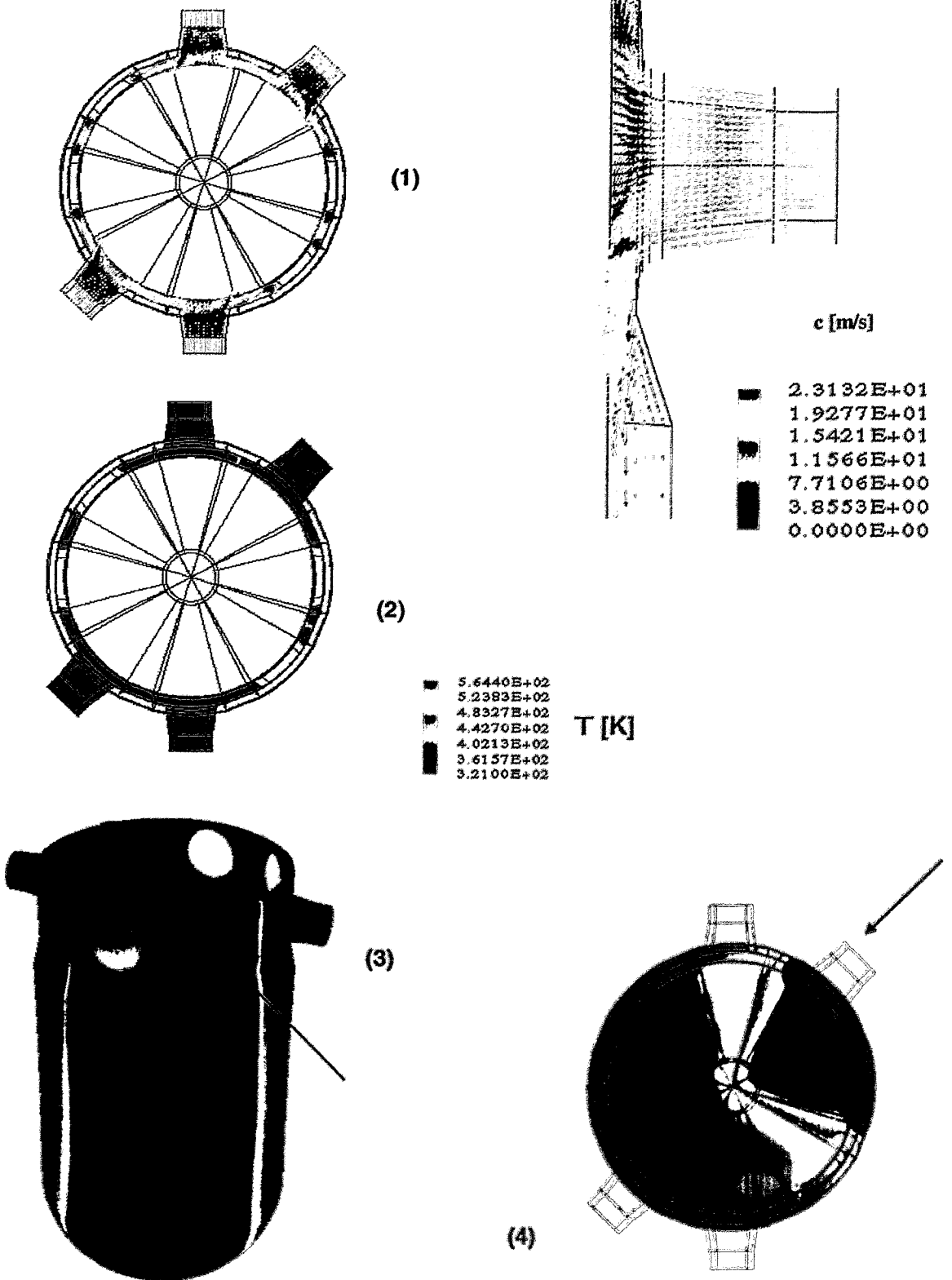
Fig. 1 Flow field in the nozzle area (1), coolant mixing in the nozzle plane (2),
downcomer (3) and the core inlet (4) of KONVOI type reactors

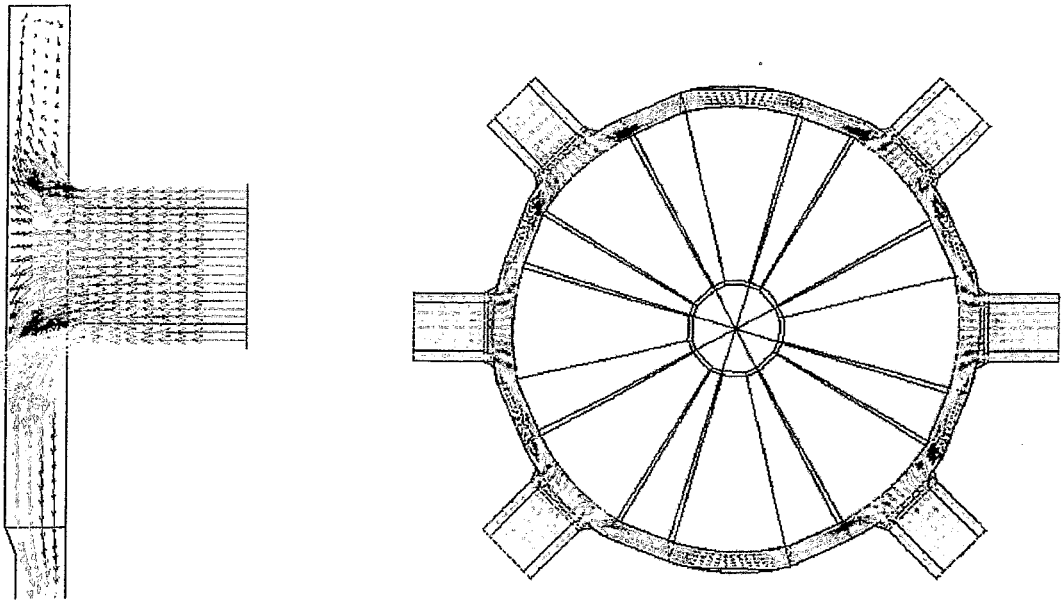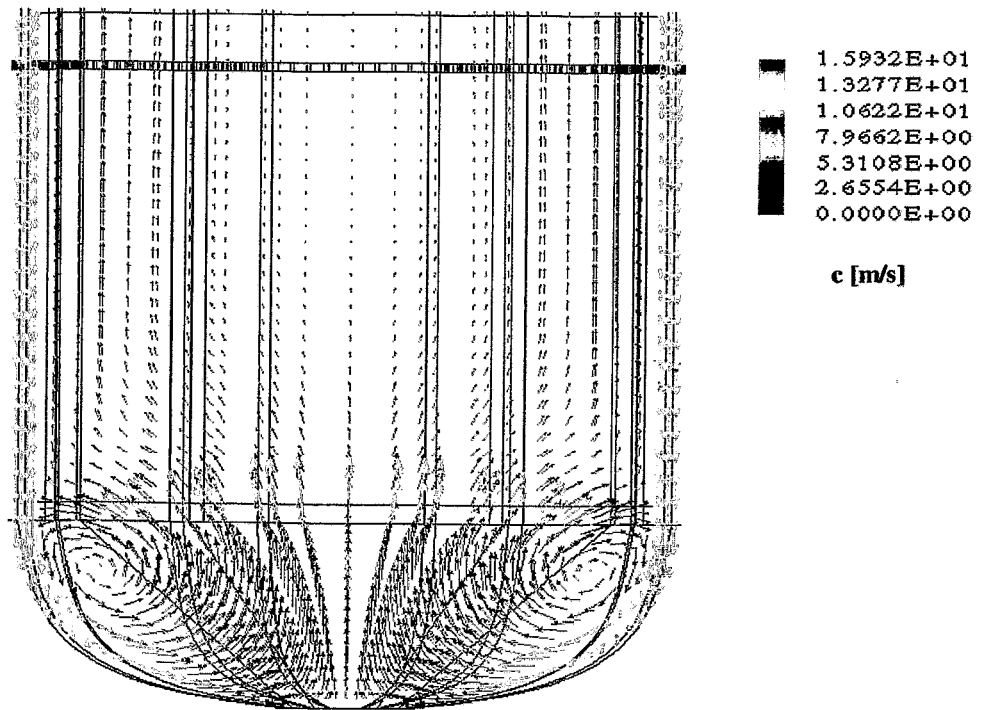$c \, [m/s]$

1.5932E+01
1.3277E+01
1.0622E+01
7.9662E+00
5.3108E+00
2.6554E+00
0.0000E+00

Fig. 2   **Flow fields of the VVER-440 in the nozzle area and lower plenum at nominal conditions**
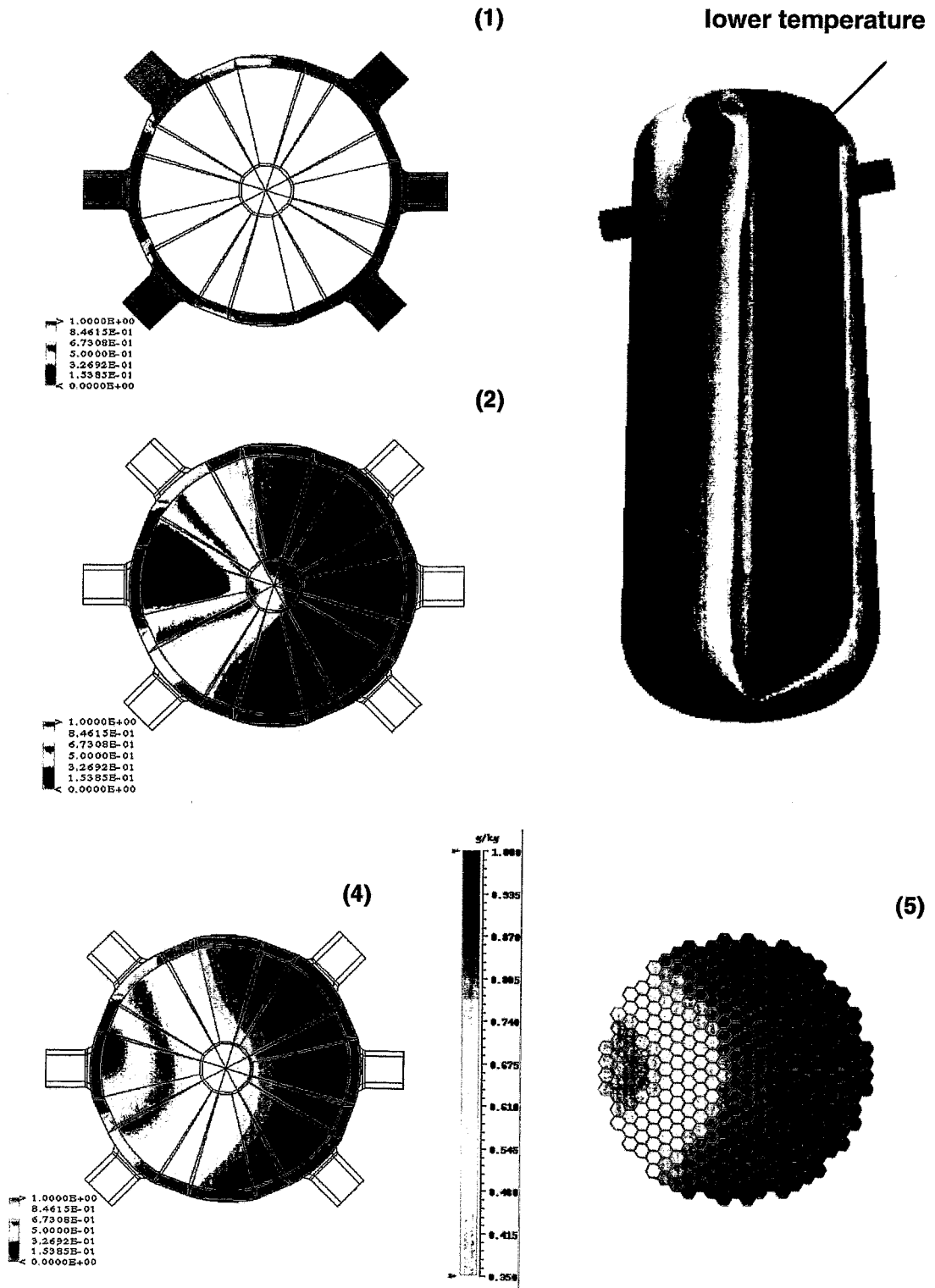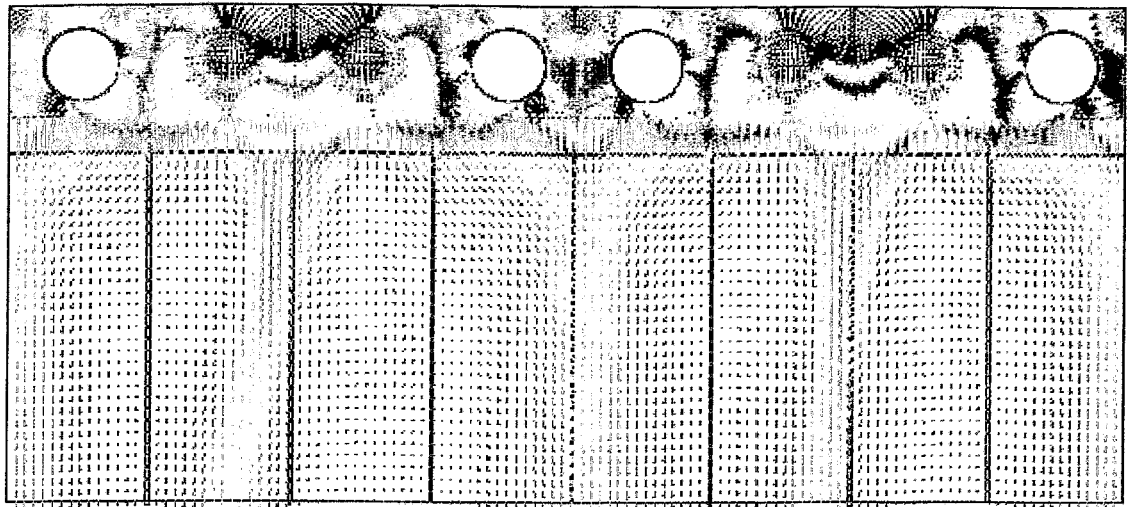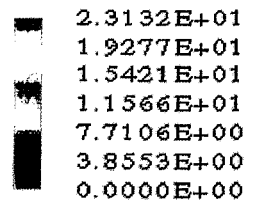
Fig. 3 Coolant mixing of the VVER-440 at the nozzle area (1) downcomer (2) perforated plate (3) and core inlet (4) in comparison with the analytical model (5)

c [m/s]

2.3132E+01
1.9277E+01
1.5421E+01
1.1566E+01
7.7106E+00
3.8553E+00
0.0000E+00

c [m/s]

1.5932E+01
1.3277E+01
1.0622E+01
7.9662E+00
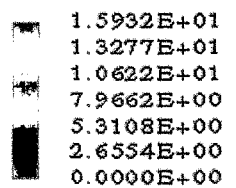5.3108E+00
2.6554E+00
0.0000E+00

Fig. 4 Flow fields in the downcomer of the PWR Konvoi and VVER-440 at nominal conditions (steady state)