ANALYSIS OF MOLTEN SALT THERMAL-HYDRAULICS USING COMPUTATIONAL FLUID DYNAMICS

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ABSTRACT

To give a good solution for the problem of high level radiocative waste partitionii transmutation is expected to be a promising option. Application of this technology also extend the possibilities of nuclear energy. Large number of liquid-fuelled reactor conc accelerator driven subcritical systems (ADS) was proposed as transmutors. Several oi consider fluoride based molten salts as the liquid fuel and coolant medium. The th hydraulic behaviour of these systems is expected to be fundamentally different than the beh of widely used water-cooled reactors with solid fuel. Considering large flow domains dimensional thermal-hydraulic analysis is the method seeming to be applicable. Since the the coolant medium as well, one can expect a strong coupling between neutronics and th hydraulics too. In the present paper the application of Computational Fluid Dynamics (CF three-dimensional thermal-hydraulics simulations of molten salt reactor concepts is introduc our past and recent works several calculations were carried out to investigate the capabilit Computational Fluid Dynamics through the analysis of different molten salt reactor con Homogenous single region molten salt reactor concept is studied and optimised. Another region reactor concept is introduced also. This concept has internal heat exchangers in the domain and the molten salt is circulated by natural convection. The analysis of the M experiment is also a part of our work since it may form a good background from the valic point of view. In the paper the results of the CFD calculations with these concepts are prese In the further work our objective is to investigate the thermal-hydraulics of the multi-r molten salt reactor.

1. INTRODUCTION

Partitioning and transmutation of actinides and long-lived fission products is a promising option to extend the possibilities and enhance the environmentally acceptable capabilities of nuclear energy. The conversion of long-lived radioisotopes to short-lived or stable nuclides requires high neutron flux. This can be realized in conventional nuclear reactors, dedicated reactors or accelerator driven subcritical systems (ADS). Several liquid-fueled reactor concepts or accelerator driven systems were proposed as transmutors. Liquid-fueled systems are flexible in the sense of fuel composition and loading into the core or defuelling. It is an important aspect to reach higher transmutational efficiency. Many of these systems consider fluoride based molten salts as the liquid fuel and coolant medium. The thermal-hydraulic behavior of these systems is expected to be fundamentally different than the behavior of widely used water-cooled reactors with solid fuel. Considering large flow domains three-dimensional thermal-hydraulic analysis seems to be applicable. Since the fuel is the coolant medium as well, one can expect a stronger coupling between reactorphysics and thermal-hydraulics.

Most of the knowledge about utilization of molten salts in nuclear reactors comes from the Aircraft Nuclear Propulsion Program (from 1946 till 1961, USA) and the Molten Salt Reactor Experiment (MSRE) program (1961-1969, USA) [1]. The only operating molten salt reactor so far was the experimental facility at the Oak Ridge National Laboratory. It was a graphite moderated thermal reactor with a nominal thermal power of 8 MW. The molten salt composition was the following (in mol percents): 70.7% ^{7}LiF - 16% BeF_2 - 13% ThF_4 - 0,3% UF_4, using highly (93%) enriched uranium [1].

In this paper an overview of the application of Computational Fluid Dynamics (CFD) for three-dimensional thermal-hydraulics simulations of molten salt reactor concepts is presented. The applied computing tool was the CFX-5.5 three-dimensional computational fluid dynamics code. It is capable of simulating forced and natural convection, heat transfer (radiation, conduction and convection), as well as single and multiphase flows in different geometry layouts. With the use of a non-structured tetrahedral volumetric mesh for the finite volume solving method almost any kind of flow and heat transfer problems can be simulated. Both steady state and transient simulations can be carried out by the numerical solution of the mass, momentum and energy equations.

2. HOMOGENOUS SINGLE REGION CONCEPT WITH FORCED CONVECTION

In this section a homogenous single region molten salt reactor will be presented. For fuel salt the 66 LiF-34 BeF_2 (mol percent) composition was chosen. The fissile material is dissolved in the carrier salt, less than 1 mol percent. This concentration is below the solubility limit [11]. The physical properties of this material are shown in Table 1. The nominal parameters of this reactor and the choice of the salt composition is based on the concept by et al. [2].

Composition (mol%)	66 LiF-34 BeF_2
Melting point [°C]	458
Specific heat capacity [kJ/kg°C]	2.34
Density [kg/m^3]	2050
Heat conductivity [W/m°C]	1
Dynamic viscosity [g/ms]	5.6

Table 1. Physical properties of the fuel/heat carrier salt [3]

The nominal parameters of the reactor are show in Table 2.

Thermal power [MW]	2500
Mass flow rate [kg/s]	10683
Inlet temperature [°C] ([K])	620 (893)
Outlet temperature [°C] ([K])	720 (993)

Table 2. Nominal parameters of the model

The power distribution in the core is approximated with the following function:

$$\dot{q}'''(r,z) = \dot{q}'''_{max} \sin\left(\frac{z\pi}{H}\right)\cos\left(\frac{r\pi}{2R}\right)$$

where H is the total height of the core (z=0 is at the lower plane), R is the maximum radius (core, z is height and r is radius. The q'''_{max} factor was calculated in every case in order to 2500 MW integral power in the core. In the next sections the results of steady state calcul: carried out by nominal conditions and by using the k-ε turbulence model will be presented.

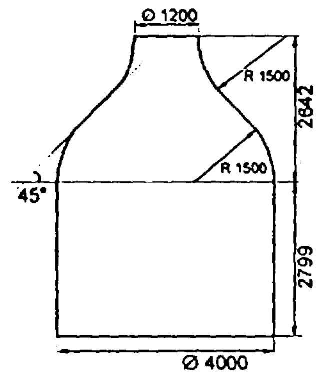

Figure 1. Geometry of the core

The geometry of the reactor core is in Fi; 1. The inlet plane is the total lower c section, a circle with a radius of 2 m. The ot is also a circle with a radius of 0.6 m. The t volume of the core is 51.365 m^3. This (geometry was extended with an ann downcomer and four inlet nozzles on the bott and an outlet nozzle on the top.

In CFX-5.5 the domain of power generat shall be exactly defined. This means the po' generation distribution has clearly defi boundaries. This is also an import approximation of these calculations.

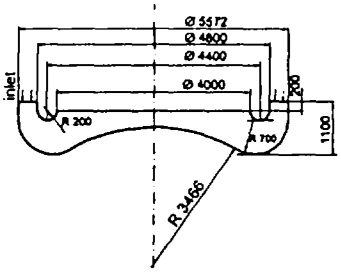

Figure 2. Geometry of the lower plenum

Figure 2. shows the geometry of the lower plenum. In Figure 4. the geometry of the annular downcomer and the four perpendicular inlet nozzles is shown. The four inlets were placed in a 90-degree symmetry.
In the next subsections the analysis of this reactor concept will be presented. Three different inlet layouts will be discussed. In the first case, the inlets are perpendicular to the downcomer. In the second and third subsections an angle of 45° and 22° is formed between the centerline of the nozzles and the horizontal, respectively.

2.1. Homogenous single region concept with forced convection, horizontal inlet nozzles

This design of the four concentrated inlets takes a strong affect on the flow field inside the core. Hereby it also has an effect on the temperature distribution.

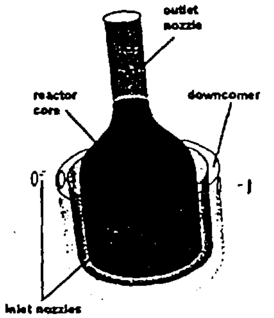

Figure 3. The reactor model

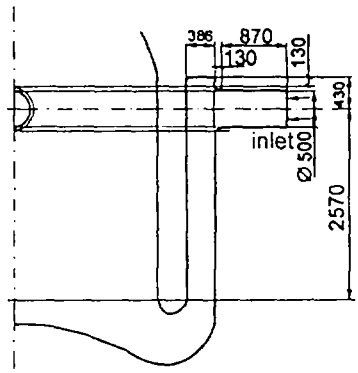

Figure 4. Geometry of the downcomer and the horizontal inlet nozzles

In the case of the horizontal – or perpendicular to the downcomer – inlets (see Figure 3.) the molten salt flows down in two separated main streams between the inlets. Under the inlets upward flow – in the downcomer this means backflow – can be seen (Figure 5.).

After turning back to the core the mainstreams with higher velocity are located in the middle of the core. As a result of this, between the core wall and the mainstreams a region of recirculation is formed. In front of the inlets, where the medium flows upward in the downcomer, there is upward flow inside the core (see Figure 6.). In the regions of re-circulation in the core the fuel spends more time heating up. Hereby large differences are formed in the temperature field, both asimuthally and radially (Figure 7.).

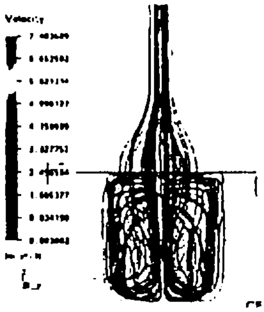

Figure 5. Streamline representation of the flow from one inlet

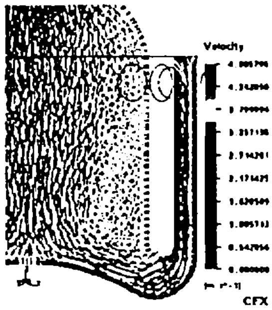

Figure 6. Vector representation of the velocity field in the symmetry plane of the inlets (upward flow under the inlets and re-circulation in the core)

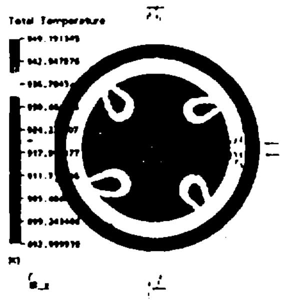

Figure 7. Temperature distribution one meter above the lower plane of the core

On Figure 8. and Figure 9. the obtained radial distributions of the axial velocity component and the temperature inside the core can be seen. These graphs show the strong coupling between the velocity field and the temperature distribution. Where the axial velocity component is negative – which means downflow – the temperature has locally higher values. It is also significant, that the radial distributions are more uniform in the upper part of the core.

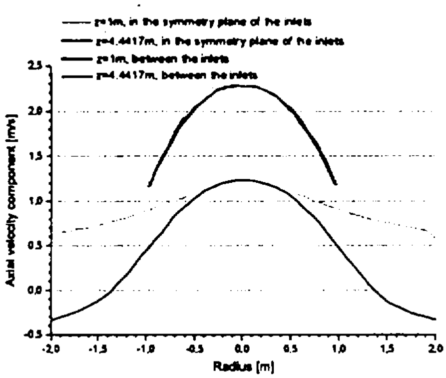

Figure 8. Radial distributions of the axial velocity component in the core (horizontal inlet)

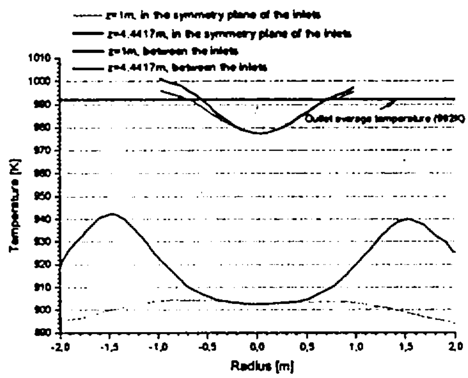

Figure 9. Radial distributions of the temperature in the core (horizontal inlet)

2.2. Homogenous single region concept with forced convection, 45-degree inlet nozzles

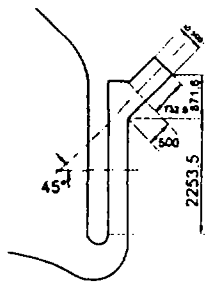

Figure 10. Geometry with 45-degree-inlet

In case of the 45-degree-inlet geometry (Figure 10.) the mainstreams go down right under the inlet nozzles. The backflow in the downcomer can be experienced again but now between the nozzles (Figure 11.). This means the characteristics of the temperature field are quite the same like in the case of horizontal inlets but it is rotated by 45 degrees (Figure 12.).

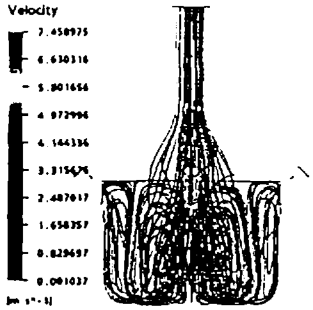

Figure 11. Streamline representation of flow from one inlet nozzle (45-degree-inlet)

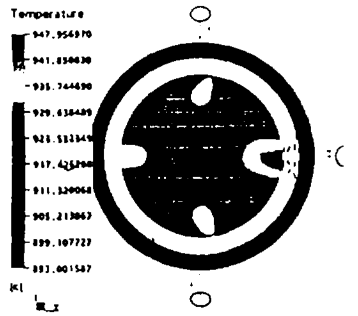

Figure 12. Temperature distribution one meter above the lower plane of the core (45-degree-inlet)

2.3. Homogenous single region concept with forced convection, 22-degree inlet nozzles

Both the flow field and the temperature distribution are more uniform, when the angle between the inlet centerline and the horizontal is 22 degrees. In this case no backflow formed in the downcomer, as it is shown on Figure 13. The flow field in the downcomer without significant upward circulation and strong mainstreams results in a less varying velocity field inside the core.

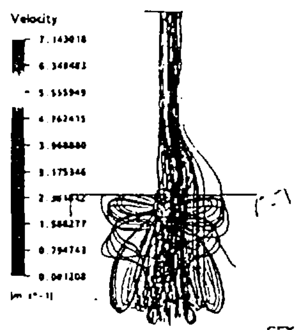

Figure 13. Streamline representation of flow from one inlet nozzle (22-degree-inlet)

The radial distribution of the axial velocity component, as well as the radial distrib the temperature is more uniform in the core than in the previous cases (see Figure 14. and The CFD investigations of different inlet layouts have shown that with appropriate inlet the maximum values of the temperature and the temperature differences inside the core decreased. In this way better uniformity of the temperature field is also obtainable.

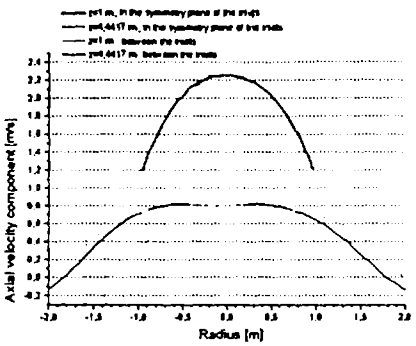

Figure 14. Radial distributions of the axial velocity component (22-degree-inlet)

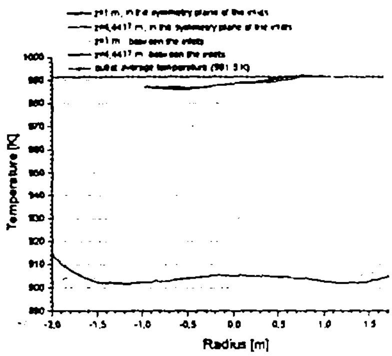

Figure 15. Radial distributions of the temperature (22-degree-inlet)

3. SINGLE REGION CONCEPT WITH INTERNAL HEAT EXCHANGERS, NATUR CONVECTION

In this section three theoretical reactor designs will be introduced. All of them l critical core with internal heat exchangers inside. The cores are simple cylinders, with sep segments for the modeling of the internal heat exchangers. In the volume of the core the nc power generation is 2500 MW with the same spatial distribution as in the previous sectio Eq. 1.). For modeling the heat exchangers smaller volumes were defined with -2500 MV sinks. With these simple layouts it was possible to carry out preliminary studies of a liquid-: reactor with internal natural circulation. For every simulation the k-ε turbulence model was

3.1. Single region concept with three internal heat exchangers, natural convection

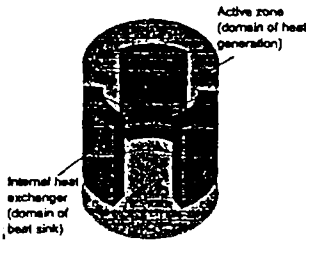

Figure 16. Model of a reactor with internal heat exchangers

The first model is shown in Figure 16. The is a cylinder with a radius of 2 m and a heigl 4.85 m. There are three volumes for mode the heat exchangers inside the cylinder of core. The geometry of the model and the la of the heat sinks are detailed in Figure 17. The dimensions of the cylinder are definec that the volume of the core is the same as in previous models discussed in section (51.365 m^3).

With this model no acceptable results were obtained with steady state simulations. A transient calculation was carried out.

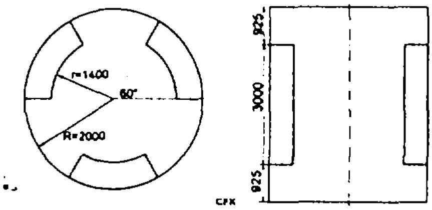

Figure 17. Dimensions of the model with three volumes for heat exchangers

After 37 s of simulation time the velocity field and the temperature field reached steady state values and characteristics. The calculated velocity field can be seen in Figure 19.
Figure 18. shows a streamline representation of the flow. The flow field is characterized by a 120-degree rotational symmetry.

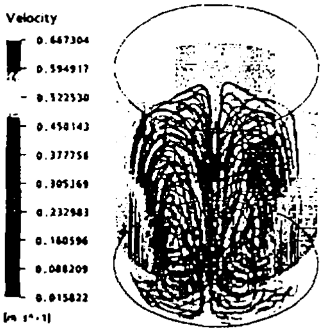

Figure 18. Streamline representation of the flow field

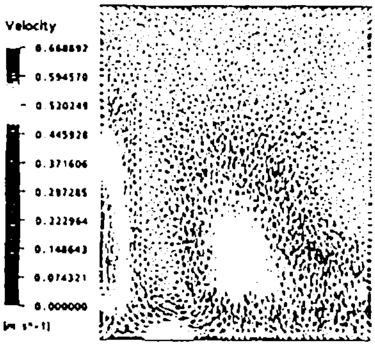

Figure 19. Vector representation of the flow field (vertical symmetry plane)

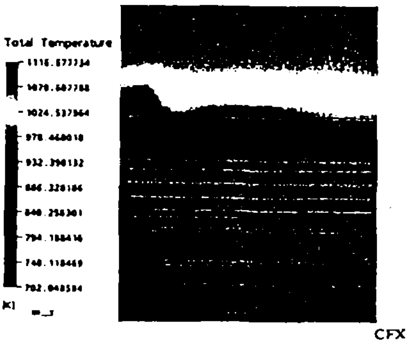

Figure 20. Temperature field (vertical symmetry plane)

In the upper region of the reactor the velocity values are very low (Figure 19.), this results in very high temperature values (see Figure 20.). The temperature maximum is 1116 K, while the minimum is at 702 K

3.2. Model with three domains of heat exchangers on the top of the reactor

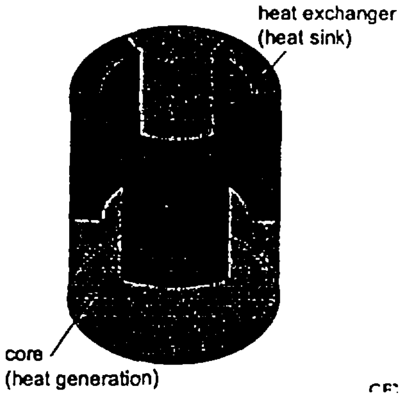

Figure 21. Model of a reactor with the internal heat exchangers on the top

The second version of the model has ; dimensions but the heat exchanger domain located at the top of the cylinder (Figure With this model steady state solution obtained. A significant rotational symmetı 120 degrees can be seen in the flow field a Downflows with the highest velocity (0.98 are located in the center of the heat exchan near the wall. Upward flow is formed iı center of the core and also near the between the heat exchanger domains.

It is significant as well that the upward near the wall is limited to the lower half o core.

In the upper half the molten salt swirls back (see Figure 22.) and has a velocity close to m/s. In Figure 23. the obtained temperature field is presented. The absolute maximum is l (1017 K) than in the previous case.

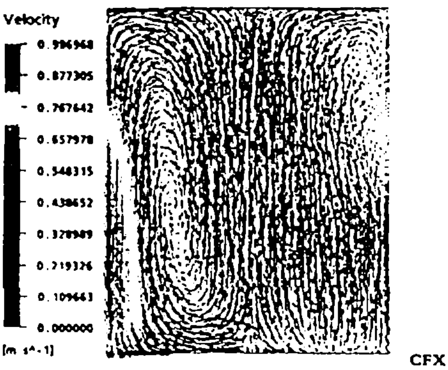

Figure 22. Vector representation of the flow field (vertical symmetry plane)

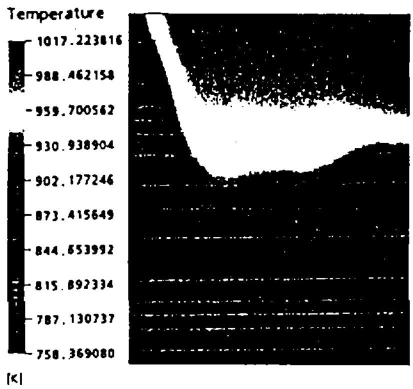

Figure 23. Temperature field (vertical symmetry plane)

3.3. Model with one heat exchanger domain on the perimeter

The next model is cylindrical, too. In this case the heat exchanger is one conti volume located on the perimeter of the core cylinder (Figure 24.). The heat exchanger is tl than in the previous cases but covers an axially larger range.

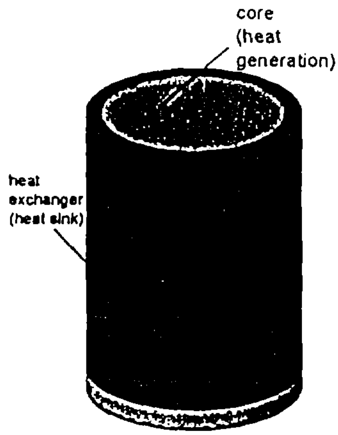

Figure 24. Model of a reactor with a one-volume internal heat exchanger on the perimeter

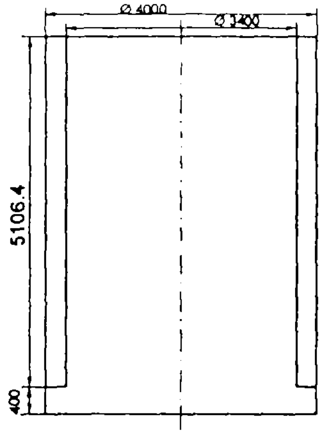

Figure 25. Dimensions of a reactor with a one-volume internal heat exchanger on the perimeter

With this geometry the flow field is cylindrically symmetric. The velocity peaks at a value of 0.52 m/s, reaches it in the upper half of the heat exchanger domain where the fluid flows downward (Figure 26.). There are two regions of back-swirl, one in the upper two-third of the core and another one in the lower third, with the latter having lower velocity. The calculated temperature field is in Figure 27. It shows a lower global maximum value (1060 K) than in the first case (section 2.2.1.) but higher than in the second (section 2.2.2.). In this layout the medium with highest temperature contacts the core wall only at the top of the reactor. It is significant as well that at the top there is a 75 K step of the temperature radially, in a relatively short range.

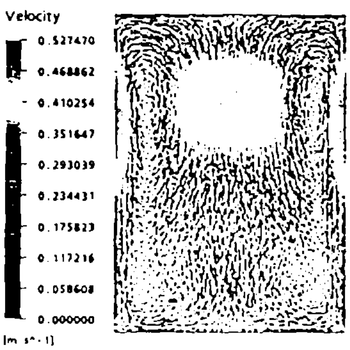

Figure 26. Vector representation of the flow field (vertical symmetry plane)

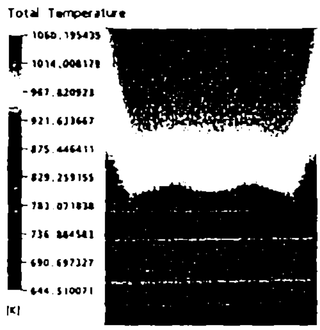

Figure 27. Temperature field (vertical symmetry plane)

Comparing the introduced models with forced and natural convection it is significant that in the case of natural circulation much lower maximum velocity values were calculated. The highest velocity value in case of natural circulation was calculated in the second case, slightly under 1 m/s (0.98 m/s). The models with forced convection have higher maximums at the inlets (6.7 m/s) and outlet (4.6 m/s) of course. But the average velocity inside the core is usually simil velocities in case of natural circulation (approximately 1 m/s).

	max. velocity [m/s]	min. temperature [K]	max. temperature [K]	$\Delta_{Tmax-Tmin}$ [K
nat. 3.1	0.67	702.0	1116.6	414.6
nat. 3.2	0.98	758.3	1017.2	258.9
nat. 3.3	0.52	644.5	1060.2	415.7

Table 3. Comparison of the three models with natural circulation

When the heat exchanger domains are located at the top lower maximum temper were calculated. This is probably because temperature stratification develops in the molten s the heat exchangers located lower, the natural convection can take away less from the temperature regions. When the upper end of the heat sink domains located higher the devel natural convection can take medium away from the stratified layer at the top with the hi temperatures.

4. MODELING OF THE MOLTEN SALT REACTOR EXPERIMENT

4.1. CFX model of the MSRE reactor

In this section the possibilities of computationally analyzing the Molten Salt Re Experiment will be presented. This graphite moderated experimental facility was the continuously operating molten salt reactor. The computational analysis of this reactor wou very useful to understand the behavior of fluid fueled systems. It also gives the possibili comparing the results of numerical calculations and the experimental values.

Figure 28. shows the design of the reactor and in Figure 29. the dimensions can be Unfortunately the available original documentation contains little information about the design of the reactor. Based on all the available data a CFX model of the MSRE was built.

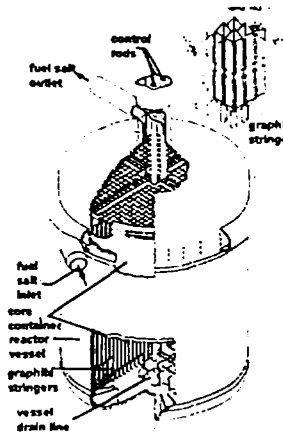

Figure 28. The vessel of the MSRE reactor [4]

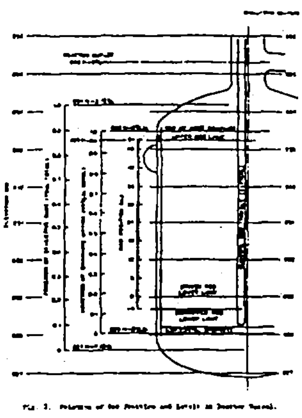

Figure 29. Dimensions of the MSRE [5]

The model contains the lower plenum (Figure 30. and 31.) with the anti-swirl vanes. The model contains 36 symmetrically placed vanes though later it was discovered that the correct number of the vanes is 48.

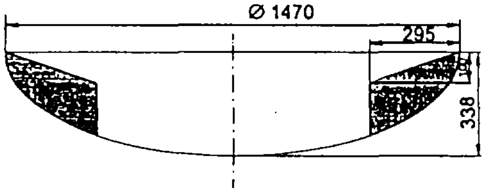

Figure 30. Geometry of the lower plenum

Figure 31. Lower plenum of the MSRE [6]

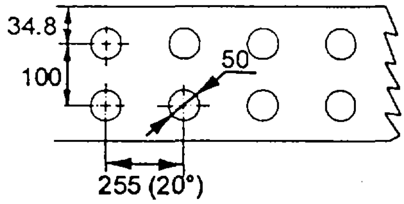

Figure 32. Geometry of the perforated wall model

The inlet flow distributor (Figure 33. and 34.) was modeled as well (Figure 32.). Due to the lack of information the design of the flow distributor in the CFX geometry is simplified. Unfortunately no information was available about the number and the design – orientation and position – of the holes on the inner wall of the distributor. Furthermore these holes are extremely small compared to the whole extent of the reactor. This condition also required the simplification of the model geometry.

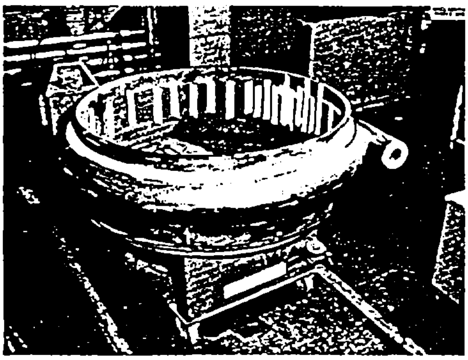

Figure 33. The flow distributor [7]

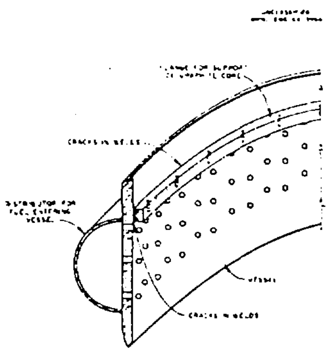

Figure 34. Sketch of the flow distributor [8]

Figure 35. Assembly of the graphite rods [6].

The core is formed of a bundle of g stringers – this is the moderator – and t molten salt, which flows through the axi. channels formed by the shape of the g rods (Figure 35.). According to th available the flow area in the core is 25% total cross section of the reactor core [4]. core there were approximately 1100 channels for fuel salt passage. The dim of these channels are 1.016 x 3.048 cm (36.). This is also extremely small comp the total size of the reactor. To build the we used the 25% area restriction. Th channels were modeled with 81 rec shaped channels with the dimensions sh Figure 37.

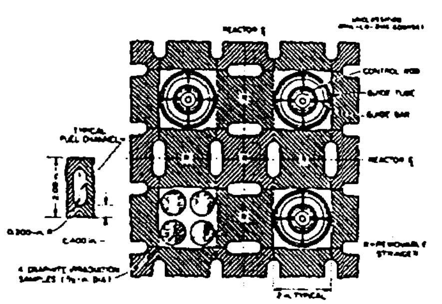

Figure 36. MSRE control rod arrangement and typical fuel channel [6]

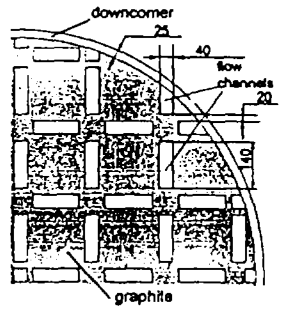

Figure 37. Geometry and layout of the fl channels in the CFX model

With the application of the available information a complex and detailed model MSRE was built. Figure 38. and 39. show the complete CFX model.

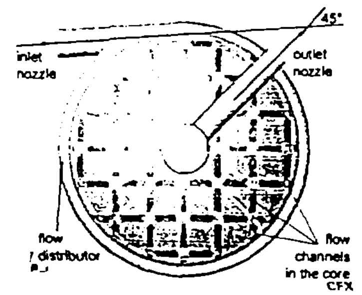

Figure 38. The CFX model of the MSRE

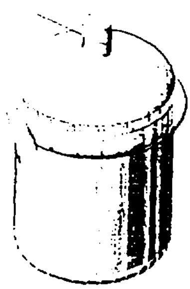

Figure 39. The CFX model of the MSR

In Figure 40. the representation of the tetrahedral volumetric mesh is shown. On the internal surfaces of the flow region inflated layers were applied. One can see that the anti-swirl vanes and the wall between the downcomer and the flow channels were modeled as thin surfaces. In a CFX model thin surfaces has no real thickness.

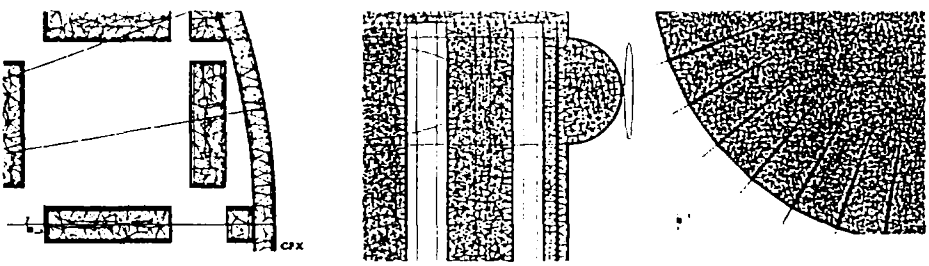

Figure 40. Meshing – in the flow channels, at the flow distributor and at the lower plenum

For the simulation only the flow regions were modeled, the materials of the structure – i.e. the steel reactor vessel and the graphite bundle – were not taken into consideration.

4.2. CFX-5.5 calculations with the MSRE reactor model

In the next section the three-dimensional CFD investigation of the MSRE will be presented. The investigation focused only on the flow properties of the reactor. Heat generation was taken out of consideration. For the simulation the k- ε turbulence model was applied.

Figure 41. shows the streamline representation of the flow in the reactor. It is significant that the fluid hardly enters the downcomer until it takes a full round in the inlet volute. This is because the perforated wall of the flow distributor prevents the fluid from entering the downcomer until it reaches the inlet nozzle. Then the pressure form the entering medium forces the salt to go trough the perforation holes. The molten salt flows down with a higher velocity in the downcomer only in a small section (Figure 42.).

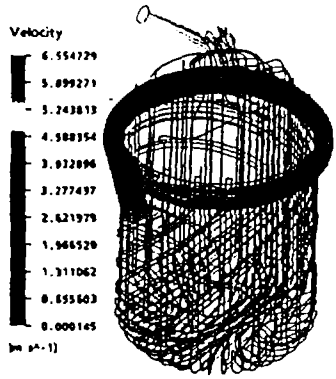

Figure 41. Streamline representation of the flow (colored by velocity values)

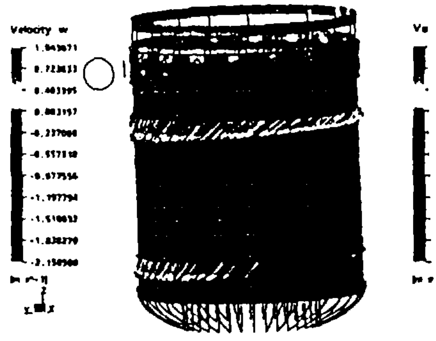

Figure 42. Axial velocity component ai velocity vectors in the downcomer

Since the flow in the downcomer is highly non-uniform the upward flow inside the core non-symmetric.

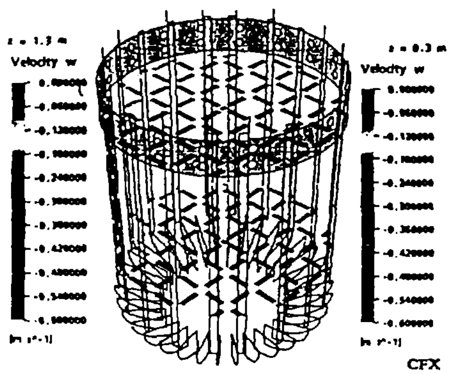

Figure 43. Values of the axial velocity component inside the core

The result of the calculation shows that i flow channels close to the inlet nozzle th flows downward, opposite to the dom upward flow in the core. In Figure 43 negative values – i.e. downward flow – o axial velocity component is shown. The t dimensional calculation has shown that reactorphysics calculations – especially in of transients (pump startup, coastdown) - CFD can be important. If the heat generati the core is needed to be considered, knowledge of the velocity field is also impo since heat transfer is velocity dependent as v

5. CONCLUSIONS AND OBJECTIVES

In the present paper an overview about three-dimensional Computational Fluid Dynamics analysis of molten salt reactors was given. Two homogenous, single region molten salt reactor concepts were introduced. One with external heat exchangers and forced convection, one with internal heat sinks and natural circulation. The calculations have shown that CFD – and the code CFX-5 – is appropriate for investigations of such systems. The results also point that three-dimensional simulations are essential in order to understand the behavior of these systems. The purpose of these investigations is to make a basis for the thermal-hydraulic examination of the multi-region molten salt reactor concept (Figure 44.) and the multi-region accelerator-driven molten salt system (Figure 45).

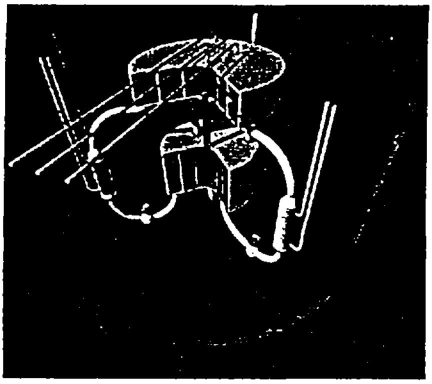

Figure 44. Concept of a multiregion molten salt reactor [9, 10]

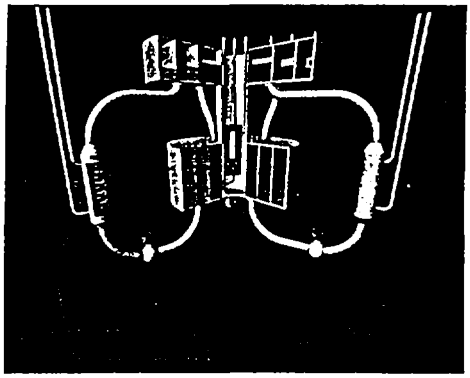

Figure 45. Concept of a multiregion molten salt accelerator-driven system [9, 10]

Despite the limited amount of information about the design of the Molten Salt Reactor Experiment operated at the Oak Ridge National Laboratory a complex and detailed CFX model of the MSRE was built. Though the obtained results need further discussion the calculation carried out with the model showed the importance of three-dimensional thermal-hydraulic analysis. More detailed description would be essential for further complex analysis of the MSRE.

The simplification of the model is also a possibility. Some of the ORNL reports suggest that the flow distribution is approximately uniform in the core, although it is based on experiments carried out with water on a full-scale reactor model [12]. Assuming a uniform flow velocity field – with a radially and tangentially constant axial and a tangential component – in the downcomer the modeling of the flow distributor is not needed. This can reduce the size of the problem. To make the model finer more but smaller flow channels could be modeled.

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