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An influence of core physics peculiarities upon the thermal hydraulics performance in Cascade Subcritical Molten Salt Reactor

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This paper presents the results of investigation of the influence of core physics peculiarities upon thermal hydraulics and workability of the main structures in Cascade Subcritical Molten Salt Reactor. Different variants of the target have been considered. Revealed it has been that the optimal variant of the target design (from point-of-view neutron efficiency + coolability) corresponds to the tight tungsten rod bundle packed in hexagonal lattice cooled by the same molten salt as being circulated in the central core zone. The limit of the power volumetric density in the tungsten rods has been defined from the thermal physics and thermal mechanics calculational estimations. The results are demonstrated of research of the central core zone thermal physics for a few variants differed by the combinations of the coolant, structures and fuel in the central zone. Different variants of circulation (forced and natural) of the coolant in the central zone have been considered from view-point of workability of the central zone structures under condition of the great power rate. The questions of workability of the Intermediate Heat Exchangers of the central and peripheral core zones for different variants of reactor design are also discussed.

KEYWORDS: molten salt reactor, central zone, transmutation zone, proton-beam target, thermal hydraulics, temperature distribution

1. Introduction

Cascade Subcritical Molten Salt Reactor (CSMSR) is assumed to consists of three main parts: accelerator-driven proton-bombed target, central and peripheral zones. External neutrons in CSMSR are generated in the central zone as a result of interaction of protons with the target nuclei. The CSMSR central zone is designed for increasing the number of these external neutrons due to their multiplication in the fuel of the central zone with high content fissile material [1].

To obtain the highest multiplication of the external neutrons and the highest neutron leakage from the central zone to the MA burning zone (peripheral zone), while not exceeding the selected reactor subcriticality level, the central zone should have fast neutron spectrum and contain as much fissile material as possible for heat removal. The main requirement to the peripheral zone is provision of neutron flux, which is optimal for MA burning. Preliminary estimates show that the optimal neutron flux should be higher than $2{\cdot}10^{15}$ n/cm^{2}s.

This requirement leads to very high volumetric power rate (1000 – 6000 W/cm^3) in all the parts of the CSMSR. To provide the workability of the core structures and intermediate heat exchangers under condition of so big level of power rate it is necessary to impose strict limitations on the temperatures and temperature gradients developed in the coolants and constructions.

In the current paper, some question concerning the thermal physical peculiarities of CSMSR target, central and peripheral core zones, influenced by neutron and proton physics specificity, are discussed.

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2. Influence of high neutron flux upon the heat transfer conditions in the Inner Core of CSCMSR

2.1 Peculiarities of thermal physics of the proton bombed CSMSR Target

Different variants of the Target material, coolant and design has been taken into account. In the result of parametric investigation it has been revealed that the most 'coolable' design of the Target (with the best ability of heat removal from the Target) corresponds to the tight Tungsten rod bundle packed in hexagonal lattice, cooled by circulated in reactor molten salt composition of (16.5)%LiF – 58%NaF – 24%BeF_2 –1.5(YF_3-ZF_3) (mol.%) (where YF_3, ZF_3 – trifluorides of MAs and FPs, respectively). The diameter of the rods and the lattice pitch are 6 and 7 mm respectively. Spacing of the rods assumed to be the same as in the typical LMFBR Fuel Assembly (wire wrapping around the rod of 'wire-to-rod' kind).

The limit of the power volumetric density in the Tungsten rods has been defined from the thermal physics and thermal mechanics calculational estimations at the level of 2 GW/m^3 in maximum. At such a high value of power rate the value of maximum tungsten rod temperature at the boundary with high-flowrate salt coolant (8 m/s) reaches 750 - 800 ^oC, the temperature head 'rod wall - coolant' can amount 90 - 100 K; azimuthal temperature deviation at the rod wall can reach 40 K. Such a set of temperature characteristics shows that tungsten rod bundle Target will work under the stressed and aggressive (from a side of the coolant) conditions.

2.2 Effect of high neutron flux and spatial power nonuniformity on temperatures of the coolant and structures in the Inner Core

A parametric investigation of thermal physics of Inner Core (IC) has been conducted in order to estimate the maximum allowable temperatures of coolant, structure materials and fuel. The variants were explored with the following combinations of the coolant, structures and fuel in the IC:

a) liquid heavy metal coolant-fuel compositions Pb-Bi-Pu and Pb-Bi-Np without the structures inside IC;
b) combination of liquid heavy metal Pb-Bi coolant together with bundle-rod lattice comprising the solid Pu-Np-N ceramic fuel clad with Hastalloy material;
c) combination of liquid light metal Na coolant together with bundle-rod lattice comprising the solid Pu-Np-N ceramic fuel clad with Hastalloy material;
d) combination of fueled molten salt coolant together with bundle-rod lattice comprising the solid Pu-Np-N ceramic fuel clad with Hastalloy material.

Common in all the listed variants of cascade multiplication zone IC was requirement of getting the high average neutron flux in the Transmutation Zone (Outer Core) at the level of ~ 1.5-2·10^{15} n/cm^2/s. The meeting of such a requirement leads to necessity to have a 4-5 times more intensive neutron flux in the Inner Core (5-8 ·10^{15} n/cm^2/s). With so high level of neutron flux the average volumetric power rate (VPR) in the IC reaches 1 – 1.5 MW/l-of-core, that a 4 - 6 times higher of maximum neutron flux, got in the LMFBR cores. And more, the maximum VPR in the IC gets 2 – 3 MW/l-of-core and even higher.

For the variant (a), which distinguishes by usage of liquid heavy metal coolant-fuel compositions like Pb-Bi-Pu or Pb-Bi-Np without the structures inside IC, it was studied the question of transfer of heat generated in IC to the Secondary Circuit inside the bound of reactor monoblock. Both natural and forced convection of fueled coolant in IC has been considered.

2.2.1 The variants with the natural circulation of the coolant in the Inner Core

Natural convection (NC) has the positive aspect, which is absence of circulation pumps working under condition of aggressive environment of liquid heavy metal (LHM) and occupying a big space inside of reactor monoblock. The calculations conducted in simulating of contour thermal hydraulics show that for getting of developed natural circulation in the IC circuit it is necessary to use rather big Intermediate Heat Exchangers (IHX) and great heating (temperature head) in the IC. The main results are presented in Table 1. One can see from this Table that even with a big heating in the IC the value of bulk coolant velocity is not sufficiently high, but the temperature head, in the contrary, is so big that the temperatures, under which structure materials work in the contact with aggressive LHM, are inappropriate high. Note, that specialists on the problem of corrosion-erosion degradation of structure materials under impact of Pb-Bi LHM and maintenance of coolant chemistry regime in the heat-exchange circuits have admitted the fact that proved can be the workability of structure materials (austenitic and ferritic - martensitic steels) under the temperatures not higher 600 ^{0}C [2]. Other double LHM systems like Pb, Pb-Mg, Pb-K and Pb-Na are in the early stage of their investigation. An information about exploration (and what's more getting of technology) of triple LHM systems like Pb-Bi-Pu or Pb-Bi-Np is absent in open literature.

Table 1. Volumetric power rate in IHX and thermal hydraulics characteristics of the Inner Core circuit under the natural circulation of the fueled Pb-alloy coolant *$^{)}$

Characteristics	Volumetric power rate in IHX = 0.03 MW / l	Volumetric power rate in IHX = 0.06 MW / l
Mean heat flux in IHX, kW/m^2	400	500
Bulk velocity of the coolant in the Inner Core, m/s	1.05	0.72
Radially-averaged heating in IC, K	570	810
Maximum temperatures of structure materials in IC circuit, ^oC	1100	1400

*$^{)}$ The results has been obtained for the following given parameters: average volumetric power rate in the Inner Core = 1 MW/l; the coolant temperature at the IC inlet = 400 ^{o}C; the height of flow riser = 3 m; the thermal-physics properties of alloy are the same as for Pb-Bi.

Note, as well, that a reason of big volumes of IHXs is low level of Volumetric Power Rate in them, that in turn is caused by the followings:

- necessity of organization of loose tube spacing of IHX for decreasing of IHX hydraulic resistance;
- impossibility of getting of high heat fluxes in IHX because of limitation of the temperature drop on the tube wall, low intensity of heat transfer at least on the side of LHM coolant and thermal resistance of the tube wall and depositions on its surfaces.

With the VPR equaled in IHX to 0.03 MW/l-of-IHX the volume, occupied with IHX tube bunch, reaches 15 m^3 to remove the power of 450 MW generated in IC. Whole IHX (or in the case of necessity to have a few smaller IHXs), accounting for its shell and inner structures, will be as minimum a twice bigger. Thus, a problem is appeared of placing of large-scale IC IHXs inside the vessel of reactor monoblock.

One can see from Table 1 that an attempt to raise the VPR in IC IHX from 0.03 up to 0.06 leads to significant decreasing of naturally-circulated coolant velocity and respective increasing of the coolant heating (IC inlet-outlet temperature head).

Thus, the removal of heat, generated in the Cascade Multiplication Zone (IC) under condition of very high VPR (1 – 1.5 MW/l-of-IC) appeared to be unlikely real in the regime of the coolant NC using the state-of-art coolant and structure material technology.

2.2.2 The variants with the forced convection of the coolant in the Inner Core

Usage of forced convection (FC) of the LHM fueled coolant can decrease a three times the heating in IC and increase visibly the magnitude of VPR in the IC IHXs (see Table 2). As one can see from Table 2 the maximum operational temperature of the contact coolant-structure becomes considerably lower in the case of FC comparatively to NC. However, the level of maximum temperatures remains still unallowable high. IXHs become a 4-6 times smaller.

Nevertheless:

- If the IC circulation pump stands on the cold leg then it is necessary to desist from free level of coolant and pressurize the circuit of IC. The pressurizer should be foreseen to compensate the coolant thermal expansion in the IC circuit as well;

- If the IC circulation pump stands on the hot leg then a problem arises of designing the high-capacity pump working under condition of high-temperature aggressive LHM fueled coolant;

So, the possibility of application of fueled liquid heavy metal systems appeared to be proven neither for the natural convection nor for the forced convection of such fueled coolant in the circuit of the Cascade Multiplication Zone (Inner Core).

Table 2. Volumetric power rate in IHX and thermal hydraulics characteristics of the Inner Core circuit under the forced convection of the fueled Pb-alloy coolant *⁾

Characteristics		Value
Volumetric power rate in IHX,	MW / l,	0.3
Mean heat flux in IHX,	kW/m^2	600
Bulk velocity of the coolant in the Inner Core,	*m/s*	3**⁾
Radially-averaged heating in IC,	*K*	190
Maximum temperatures of structure materials in IC circuit,	^oC	700

*⁾ The results has been obtained for the following given parameters: average volumetric power rate in the Inner Core = 1 MW/l; coolant temperature at IC inlet = 400 ^oC; thermal-physics properties of alloy are the same as for Pb-Bi.
**⁾ Maximum allowable level of velocity of liquid heavy metal coolant in the known heat transfer circuits.

2.2.3 The variants with the solid-fuel insertion in the Inner Core

Three variants have been considered of the Inner Core with the solid-fuel insertion, which is designed as bundle-rod lattice comprising the solid Pu-Np-N ceramic fuel clad with Hastalloy material. Those variants differ by the kind of supposal coolant:

- fueled molten salt composition 16.5%LiF-58%NaF-24%BeF_2-1.5%MAF_3 ;
- liquid heavy metal composition on the base of lead;
- liquid light metal - sodium.

In order to estimate an influence of fuel rod bundle tightness upon the level of maximum temperatures of the coolant and rods two cases of fuel lattice has been considered:

- very tight lattice (with the pitch-to-diameter ratio of 1.16);
- looser lattice (with the pitch-to-diameter ratio of 1.32).

In Tables 3 and 4 the temperature characteristics of the coolant and rod claddings for both cases of the fuel lattice are presented. In Tables 5, 6 the geometrical characteristics of the fuel rod and its temperatures in the place of the maximum Inner Core VPR are demonstrated.

As one can see from Tables 3 and 4 the heating in the IC fuel rod bundle is too big. Maximum temperatures of cladding outer surfaces in all variants, but variant with sodium coolant and lattice with p/d-ratio of 1.32, are inappropriate great. From Table 5 it is seen that unallowable high (more than 100 ^0C) is the temperature drop on the cladding thickness. Due to huge temperature drop on the gas gap it becomes possible appearing of very high azimuthal temperature irregularities caused by the fuel pellet's eccentricity.

From the Table 6 one sees that in all cases of fuel lattice + coolant design, but variant with sodium coolant and lattice with p/d-ratio of 1.32, the maximum fuel temperature exceeds melting point. But, unfortunately, even this most coolable variant is not quite appropriate. Because, inappropriate great temperature gradients in the rod claddings still remain; inappropriate high temperature drop realizes on the thickness of the wall, bounding the Inner and Outer Cores.

So, at the present moment it is unlikely to reach high efficiency of cascade multiplication, because it requires having a very high level of neutron flux (5-8 $\cdot 10^{15}$ $n/cm^2/s$) and hence too high level of the volumetric power rate in the Inner Core (1 – 1.5 MW/l-of-IC), and such intensive heat production could not be reliably removed on the basis of nowadays level of the reactor technologies.

Table 3. Maximum heating in the Inner Core with the fuel rod bundle insertion cooled with different kinds of coolant

Coolant	Maximum heating, K	
	Pitch-to-diameter ratio s/d = 8 / 6.9	Pitch-to-diameter ratio s/d = 9.1 / 6.9
Fueled molten salt (6 m/s) entering into IC with T_{inlet} = 650 °C	210	110
Na (9 m/s) entering into IC with T_{inlet} = 300 °C	720	370
Pb-Bi (3 m/s) entering into IC with T_{inlet} = 300 °C	1200	600

Table 4. Maximum fuel rod cladding temperatures in the Inner Core with the fuel rod bundle insertion cooled with different kinds of coolant

Coolant	Maximum fuel rod cladding temperatures, K	
	Pitch-to-diameter ratio s/d = 8 / 6.9	Pitch-to-diameter ratio s/d = 9.1 / 6.9
Fueled molten salt (6 m/s) entering into IC with T_{inlet} = 650 °C	1100 °C	880 °C
Na (9 m/s) entering into IC with T_{inlet} = 300 °C	1050 °C	710 °C
Pb-Bi (3 m/s) entering into IC with T_{inlet} = 300 °C	1550 °C	1000 °C

Table 5. Geometry of the IC fuel rods with Pu-Np-N ceramic fuel and temperature gradients in the fuel rod components in the place of IC power rate peak

Geometry of the fuel rod		
Outer diameter,	mm	6,9
Cladding thickness,	mm	0,45
Initial radial gas gap (in the hot state),	mkm	50
Fuel pellet diameter,	mm	5,9
Temperature gradients in the fuel rod components in the place of IC power rate peak		
Temperature drop at the cladding,	K	130
Temperature drop at the gas gap with uncertainty due to pellet eccentricity,	K	1000 ± 700
Temperature drop in the fuel,	K	700

Table 6. Maximum fuel (pellets of Pu-Np-N ceramic) temperatures in the Inner Core with the fuel rod bundle insertion cooled with different kinds of coolant

Coolant	Maximum fuel temperature, °C	
	s/d = 8 / 6.9	s/d = 9.1 / 6.9
Fueled molten salt (6 m/s) entering into IC with T_{inlet} = 650 °C	Higher $T_{melting}$	~ $T_{melting}$
Na (9 m/s) entering into IC with T_{inlet} = 300 °C	Higher $T_{melting}$	~ 2400
Pb-Bi (3 m/s) entering into IC with T_{inlet} = 300 °C	Higher $T_{melting}$	Higher $T_{melting}$

3. Calculational analysis of the temperature distribution in the side Outer Core wall and the wall, separating the Inner and Outer Cores

3.1 The method of research

The calculational research of the temperature spatial distribution in the sidewall of the Outer Core and the wall, separating the Inner and Outer Cores, has been got as a result of solution of the conjugate problem of 2D thermal hydraulics in the Inner and Outer Cores together with task of heat transfer in the walls. Calculations were conducted on the basis of numerical model coded in TG-3D computer program [3]. There the equations of mass, momentum end energy conservation were solved in a system with molten-salt state equation and turbulent completing relations. It is assumed that the flowing medium is: a) one-phase, b) thermally expanded but not adiabatic-compressed, c) Newtonian viscous, d) Fourier thermal-conducting liquid.

Finite-volume discretization of the system of the constitutive differential equations is performed on the staggered nodal net. In the center of a scalar-value mesh the volume-average temperature and pressure are determined; in the centers of its faces the components of velocity are determined as averaged in the staggered meshes. In the current study the terms concerning the turbulent exchange by momentum and heat was embedded. A simple model of eddy viscosity was applied basing on the empirical closure for turbulent mixing length, the second invariant of the strain-rate tensor and modulus of velocity vector.

3.2 The model of reactor

The sidewall of Outer Core is considered to be empty cylinder, closed at the top and the bottom (Fig. 1). Coaxially to Outer Core cylinder the Inner Core as cylinder of a smaller radius is situated opened at its lower and upper edges. Two cylinders exchange each other by the heat going through the separating wall. The case of consideration was the cooling of IC and OC by the same molten salt (16.5%LiF-58%NaF-24%BeF_2-1.5%MAF_3).

3.3 The temperatures of the Inner and Outer core walls obtained in the results of calculations

In Fig. 2 the picture of streamlines in reactor cores is presented. The flowrate G=1.4·10^4 kg/s with the bulk velocity of 1 m/s goes into reactor from the annular slot near the lower butt of the Outer Core (Fig.1).

The temperature of the OC sidewall declines from the OC entrance upward to its outlet. Such an unusual behavior is caused by the backward clockwise stream along the sidewall due to appearing of the large-scale eddy laying on the sidewall. The maximum wall temperature does not exceed 750 ^oC. Near the inlet and outlet slots it is seen considerable axial temperature gradients (Fig. 3) that causes of quite big stresses developed in the side wall in these regions.

The temperature of the wall separating the Inner and Outer Cores do not exceed 700^{o}C (see Fig. 4). Variation of this temperature along the wall does not go beyond 40^{o}C. Small temperature spikes observed to be in the region where the main stream separates from the IC wall.

Thus 2D r-z calculations showed quite appropriate temperature regime of the wall, separating the Inner and Outer Cores in the case of flowing of the one molten salt in both reactor zones.

4. The problems of designing and substantiation of workability of the CSMSR main Intermediate Heat Exchangers

A series of parametric calculations has been conducted of thermal hydraulics in the main Intermediate Heat eXchanger (IHX), where the heat generated in the reactor transmutation zone is transferred to the molten salt (NaBF4 92%mol-NaF 8%mol) of Intermediate Circuit. The main goal of such research is revealing of peculiarities of heat transfer in IHX and accomplishing of a preliminary optimization of its design.

In the result of calculations it can be concluded the following:

One of the most important peculiarity is low heat transfer capability in the IHX because of low heat transfer coefficients from the sides of both circuits. The main reasons of this are low thermal conductivity (0.7 - 1 W/m/K) and very high viscosity (3-15·10^{-3} Pa·s). Under nominal operation condition the value of the bulk velocity on the both sides of the IHX tube wall can be in the range of 2–5 m/s. This area of velocities relates to the zone of Re number 2000 - 5000 that is the region of transition between laminar and turbulent flowing regime. The fact of low heat transfer and thermal hydraulic instabilities of laminar-turbulent regime was reported in the work [4], generalized the experience of designing and operating of MSRs.

To economy the heat transfer surfaces and the IHX tubing volume under condition of low heat transfer coefficient between the coolants of the primary and secondary circuits (a 5 times lower then in IHX of typical LMFBR) it is necessary to have:

- tight package of IHX tubes with their small diameter (not bigger 1 cm);
- as high as possible velocities on the both sides of tube, taking into account the velocity limitation because of corrosion-erosion impact of the molten salt upon the tube wall material (2.5 - 3 m/s);
- as high as possible temperature head between primary and secondary coolants taking into account a limitation on temperature gradient in the tube wall;
- long enough length of the IHX tubes (not less than 5 m).

The requirement of tightness of the tube bunch and high values of coolants' velocities leads to big pressure losses in IHX for friction. So, there should be an optimum in the construction of IHX, which matches contradiction between minimization of heat transfer surfaces (and hence minimization of IHX volume) and minimization of the pressure losses (and hence pump's power demand, sizes and reliability).

5. Conclusion

In the result of research of thermal physics problems of the CSMSR reactor core and structures the following can be concluded.

- High volumetric power rate in the Inner Core leads to necessity of applying the forced pumping of the coolant with high flowrate and velocity in order to low the coolant and structures temperatures and temperature gradients;
- A possibility of application of the fueled liquid heavy metal systems appeared to be not proven either for the natural convection or for the forced convection of such fueled coolant in the separate circuit of the Cascade Multiplication Zone (Inner Core).
- The most coolable variant of the Inner Core is a combination of the sodium coolant and fuel-rod bundle insertion. But, the main problems of this variant relate with high temperatures and temperature gradients in the structure components of the fuel rods (claddings and pellets).
- Two-dimensional calculations showed quite appropriate temperature regime of the wall, separating the Inner and Outer Cores in the case of flowing of the one molten salt in both reactor zones. The temperature distribution at the Outer Core side wall demonstrated quite big temperature gradients near the inlet and outlet of it, that can result in appearing of high temperature-induced stresses in the wall.
- The Intermediate Heat Exchangers of reactor have the number of problems to be solved and main of them relate with resistance of structure materials to high-temperature aggressive coolant and providing of tube bundle compactness under condition of low volumetric power rate in IXHs.

References

1) P. Alekseev, A. Dudnikov, P. Fomichenko, V. Nevinitsa, A. Sedov, S. Subbotin, A. Vasiliev, A. Voloshchenko."Computational Justification of Cascade Scheme of the Subcritical Molten Salt Reactor", Proc. Int. Conf. "Radioactive Waste and Spent Fuel Management", Plovdiv, Bulgaria, November 20-24, 2004.
2) P.N. Martynov, Yu.I.Orlov, A.D.Efanov, V.M.Troyanov, A.E.Rusanov. "The Technology of Lead-Bismuth coolants for Nuclear Installations", Proc. of Conf. "Heat and Mass Transport and Properties of Liquid Metals", IPPE, Obninsk, Russia, Oct. 2001.
3) E.M.Aisen, A.A.Sedov, "Modeling of 3D heat transfer and hydrodynamics in the Cascade Subcritical Molten Salt Reactor", Proc. of Conf. "Development of the multidimensional thermal hydraulics codes", IPPE, Obninsk, Russia, May 2003.
4) "Molten-Salt Reactor Program", Semiannual Progress Report Period Ending August 31, 1971, ORNL-4728.

Figures

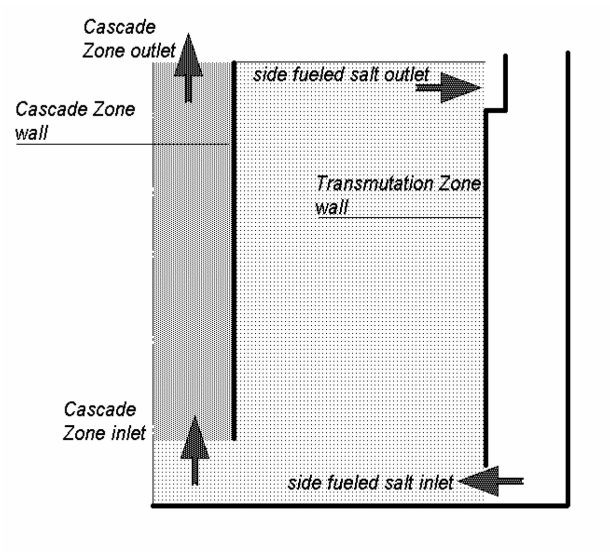

Fig. 1. The model of reactor.

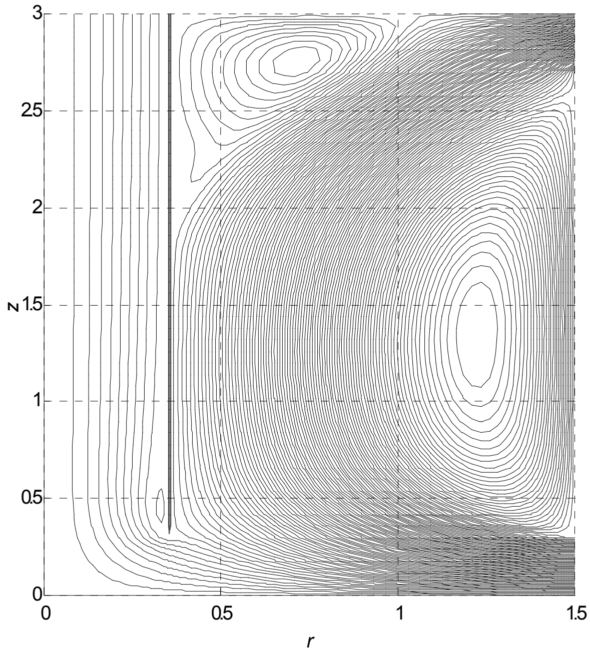

Fig. 2. Streamlines, $\Delta\psi = 195$ kg/s

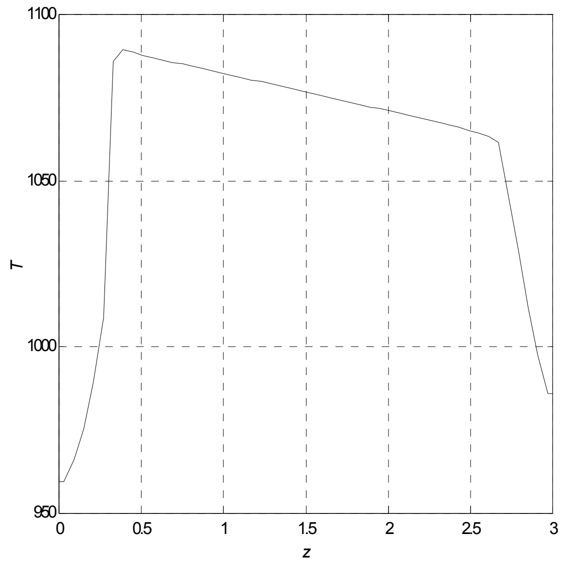

Fig.3. Temperature of Outer Core sidewall, K

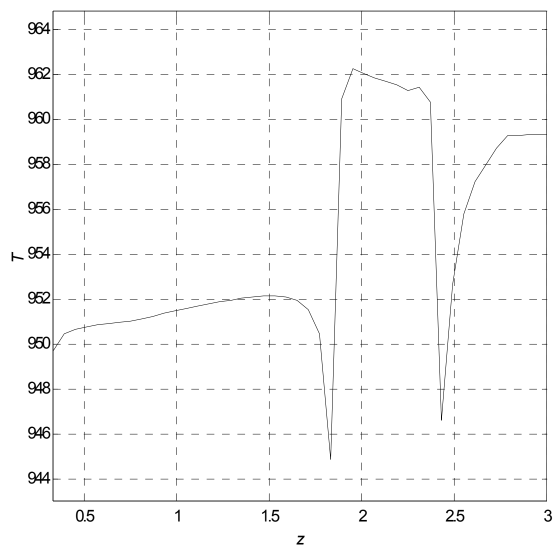

Fig.4. Temperature of outer surface of the wall separating the Outer and Inner Cores, K