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Thermo-physical properties and phase composition of full-scale corium of fast energy reactor

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Abstract : This paper has studied the phase composition and determined thermal properties of full-scale fast power corium at a room temperature. The obtained data of the corium thermal properties can be used for calculating temperature fields during modeling the processes for retentionof corium melting in the nuclear reactor core.
Keywords : fuel and structural materials of nuclear reactor core, corium, thermal properties of corium.

Introduction

At present increased attention is paid to the problem of nuclear reactors operation safety. Generally accepted, thataccident occurnce accompanied with core materials melting is a rare event. It can happen under the unique concatenation of circumstances, namely, during thsimultaneous failure of thlarge safety elements in the result of which the cooling system operation is broken or heat carrier loss occurs.

In this case, the heat released from fission reaction can lead to destruction of the core geometry and its melting. For a full assessment of the risk of using reactors and safety improvingit is necessary to predict possible course of an emergency, and to determine the possible consequences of severe accidents and measures to address them.

As is generally known, corium thermal properties (TP)[1-6]obtained during the experiments of modeling severe accidents at nuclear reactors are some of the most important and the least studied properties.

Such information can be extremely useful not only to identify the mechanisms of severe accidents, but also for the experimental studies. Therefore, a detailed study of the corium properties, including thermal onesis necessary to create a database that could be used for predicting the severe accidents going on and also in the design models.

Within the framework of the mentioned work the experiments are done on PGR[7-11]in the Institute of Atomic Energy the National Nuclear Centerof the Republic of Kazakhstan to examine the fuel behavior under a severe accident conditions.

Theobjectiveofthegivenworkistheexperimentaldeterminationoffull-scalecorium TP(hardened mixture of uranium dioxide and steel), fastpower reactor, got in the result of conducting an experiment in PGRto melt model fuel assembly (FA) in the ampoule irradiation device.

Research Methodology

To achieve the data of thermal properties of materials hardened melt of the core zone of the fast power reactorwe have carried out internal reactor experiment to get an ingot of the full-scale corium. Corium melting components was done , developed by us ampoule irradiation device in research pulse graphite reactor (PGR). Theampouledeviceconsistsofthefollowingmajorelements: FA hoodwith the inside fuel assembly of BN-350 reactor fuel elements, inner shell, pressure vessel, expansion tank, melt receiving trap.The basic properties of the fuel elements of the reactor BN-350used in the experiment are shown in Table 1.

Table 1. The properties fuel elements used in the experiment

Properties	Properties values
1. Fuel type	UO_2uranium dioxide tablets
2. Fuel Enrichment on 235U in the active body, %	17
3. Fuel Enrichment on 235U to blanket parts of the body, %	0.27
4. Fuel gravity, g/sm3	10.3…10.8
5. The outer diameter of the fuel pellet, mm	5.90 ± 0.02
6. The inner diameter of the fuel pellet, mm	1.5
7. Material cladding	0Cr16Ni15Mo3Nb Steel
8. The shell diameter (outer/inner), mm	6.9 / 6.0
9. Shell length, mm	465
10. The ratio of fuel mass in the active fuel to the mass have become	4.3 / 1.0

Intheresultoftheexperimentwegotafull-scalecoriumingotwhichexternalviewisshowninFigure1.Sample work pieces(the cylinders of about 8 mm height) were collected by drilling the got ingot with a core drill under water cooling. ThesampleworkpiecesNo.1, 2, 5, 6, 7 gotby wet grinding were grinded up to the height of ~4,5 мм. Sample workpieces No.3 andNo. 4 were not changed. The pictures of got sample work pieces(cores) of prepared samples are shown in Figure 2.

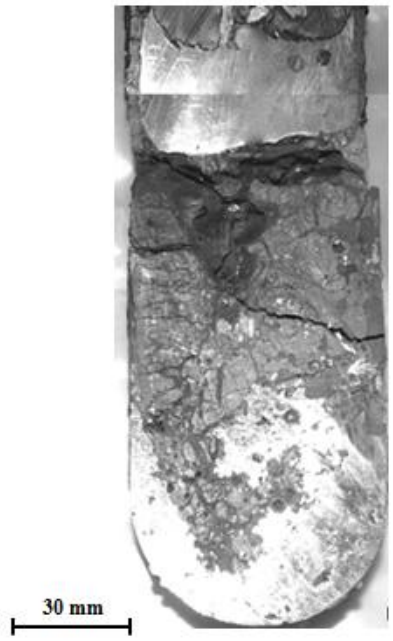

Fig:(1).Corium ingot external view

Fig.(2)External view of drilled cores No.3 andNo.4 and prepared samples No.1, 2, 5, 6, 7

X-ray phase analysis of the samples was done on Empyreandiffractometer c using Cu-radiation ($\lambda_{K\alpha1}$ = 0.154060 nm).

Diffraction patterns were got with the use of "HighScore" software for processing and searching. Shooting was done without rotation, in the fixed position of the samples. The orientation of the sample sex a mined surface was done in the object plane so that a definite orientation on the sample surface was placed parallel and perpendicular to the direction tube- goniometer axis – detector.

Heat-transfer properties ofthegotcoriumweremeasuredonUTFI-2 laboratory plant of heat-transfer properties measures.

Determining heat-transfer properties of the corium samples on UTFI-2 plant we used the methodology[12], based on the known "flash" method.ThemainpointofthemethodologyrealizedonUTFI-2 plantisthatoneendofa planar sample isheatedbyshort-term exposure to heat pulse and the registration of temporary temperature dependence on the opposite sample end.

A disk sample of sintered uranium dioxide wasusedasan auxiliary sample.

Results and Discussions

The analysis of diffraction patterns from the samples surfaces has revealed UO_2, uranium dioxide withface-centered cubic lattice as a major crystalline phase. Major phase picks are narrow with allowed $K\alpha_{1,2}$-duplet on the diffraction patterns of all samples. Theratioofphaselinesintensitiesinallsamplesconsiderably differfromtheratioofthe phase lines intensity in the data base, which testifies the presence of crystallites primary orientation in the samples of the section of metallic and ceramic structural components of the ingot.

In the result of there search we found out the phase lines α-(Fe(Ni,Cr)), γ-ironγ-(Fe,Ni,Cr)). Upon the results of the microstructure examination metal contamination share in the samples is1.5-2.5 % average, we did not observe a considerable dispersion of metal contamination on the sample surfaces.

The elemental analysis of the contamination revealed that the basic elements of the chemical composition are the components of chromium-nickel stainless steel in descending order of Fe, Cr, Ni, Mn content.

As the results of the texture characterization showed, samples No.1, 2, 5 are characterized with moderate homogeneous structure without large grains. The dispersion of relative intensities of uranium dioxide lines is close to thestandard one.

Samples No. 6, 7, on the contrary, are featured with strongly heterogeneous structure with large grains.The intensity lines distributions within the range of eachdiffraction pattern have considerable deviations from the equilibrium,the level of maximum intensity for certaindiffraction patterns differs up to 10 times. Different lines correspond to maximum intensities within the range of each end, and between the ends generally.

Table 2shows the results of measuring the diameter*d*, thickness *l*, mass*m*,and determining the density ρof the sample material used for measuring as the main ones.Table 3shows the results of determining thermal diffusivity*a*, specific heat capacity *C* and thermal conductivity $\lambda$for all samples of corium and uranium dioxide.

Table 2.Results of samples parameters measures

Sample	l, mm	d, mm	m, г	$\rho_г$, g/sm$_3$	$\rho_{об}$, g/sm^3	ε, %
No.1	4.17±0.07	10.88±0.08	3.881±0.001	10.54±0.02	10.01±0.12	8.7±1.1
No.2	4/.14±0.02	10.77±0.14	3.469±0.001	9.85±0.01	9.20±0.23	16.0±2.1
No.5	3.57±0.01	10.79±0.24	2.849±0.001	9.90±0.01	8.73±0.39	20.3±3.5
No.6	4.08±0.01	10.77±0.10	3.822±0.001	10.53±0.01	10.30±0.19	6.0±1.7
No.7	4.11±0.01	10.89±0.07	3.981±0.001	10.54±0.01	10.40±0.16	5.2±1.4

Table 3.Results of determining thermal properties of thecorium samples and uranium dioxide

Образец	ρ, g/sm^3	a·10^{-6}, m^2/s	C, J/(kg·K)	λ, W/(m·K)
No.1	10.01±0.12	2.50±0.01	294±2	7.42±0.03
No.2	9.20±0.23	1.77±0.01	327.9±0.9	5.63±0.01
No.5	8.73±0.39	1.67±0.03	432±4	6.82±0.06
No.6	10.30±0.19	1.67±0.02	451.1±1.3	7.72±0.09
No.7	10.40±0.16	2.01±0.03	365±5	7.56±0.13
UO_2	10.36±0.02	2.64±0.04	247.6±0.4	6.72±0.08

The measure results in Table3, showed the following. TP (thermal properties) of corium samples at a room temperature are evaluator close to the samples of uranium dioxide pellets.For all corium samples *a* measured values are 1.1 – 1.6 times lower than the values for the uranium dioxide. For all corium samples *C*values are 1.2 – 1.8 times higher than the values for the uranium dioxide.

TP of sample corium differ significantly. The samples with the most hydrostatical and volume densities have the most thermal conductivity resultant values. Where upon, we are worried about abnormal high heat capacity values that is difficult to explain with the samples material properties.

The use of the uranium dioxide as the auxiliary ones may cause systematic errors of the measurement results connected with the TP difference of the main and auxiliary samples. Meantime, there is the correlation between the measures values of, thermal conductivity, density, and heat capacity of the samples of the corium itself. The values of thermal diffusivity and thermal conductivity are lower and the ones of heat capacity are higher for the samples with less density.

Asa first approximation we can point out the following factors of different TP influence of the main and auxiliary samples:

1. The samples heat capacity difference must result in unequal distribution of thermal energy pulse got by each sample under the final temperature equalization. Taking into consideration this fact must result in too low values of the main sample heat capacity when the auxiliary sample with lowerheat capacity is used.

2. The samples heat capacity difference must result in inequality of heat pulse energy share got by each sample. Taking into consideration this fact must result in over evaluated heat capacity values of the main sample with using the auxiliary one with higher thermal conductivity. Whereupon the influence of the factor on the result of heat diffusivity has not been determined.

Conclusion

The results of X-ray phase analysis have revealed that the basic constituent of all corium samples is uranium dioxide, UO_2, with estimated lattice parameter a = 0,547 nm (~99% ofmass), the second constituent is the phase on the basis of ferrite,α-Fe(Ni,Cr,…), which content is from 1 up to 2 %.

As the research results have shown, samples No.1, 2 and 5 are characterized with moderate homogeneous structure without large grains. The distribution of relative intensity lines of uranium dioxide is close to standard.

SamplesNo.6 and7, on the contrary, are characterized with strongly heterogeneous structure with large grains. The distribution of lines intensity within the range of each diffraction pattern deviates significantly from the equilibrium one; maximum intensity level for certain diffraction pattern differs up to 10 times. Different lines correspond to maximum intensities, within each end surface as well as between the surfaces in general.

In the result of the carried out measures we can conclude the following:

1. We have carried out TP precheck of full-scale corium samples on the fast neutron reactor at a room temperature. The got coefficient values of heat diffusivity, specific heat capacity, and thermal conductivity will be used for TP changes examining in the selected temperature range.
2. The analysis of the results of the corium samples TP determination at a room temperature has shown the proximity of the corium thermal parameters to the uranium dioxide pellet material. Thevaluesofcorium specific heat capacity in all samples is higher than in the uranium dioxide pellets; thermal diffusivity values are lower, thermal conductivity are higher for more dense samples.
3. The analysis of the results of determining the corium samples TP at a room temperature has shown the significant differences in heat diffusivity and heat capacity for the samples.
4. There is a significant correlation between the measured values of the samples heat diffusivity and heat capacity, which can be caused by the systematic error that was not taken into account earlier. This error causes overstating the heat capacity values while the decreasing of the material heat diffusivity.

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