Nuclear Engineering and Design 322 (2017) 27–31

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Thermal properties of prototype corium of fast reactor

N. Mukhamedov [a,*], M. Skakov [b], I. Deryavko [b], I. Kukushkin [b]

[a] Shakarim State University, 20a Glinky St., 071400 Semey, Kazakhstan
[b] Institute of Atomic Energy of NNC RK, 10 Krasnoarmeyskaya St., 071100 Kurchatov, Kazakhstan

HIGHLIGHTS

- Developed the technology of manufacture the ingot of the prototype corium of fast reactor.
- Made the prototype corium of the fast reactor with the sodium coolant.
- The obtained data on thermophysical properties of prototype corium of fast reactor.

ARTICLE INFO

Article history:
Received 14 February 2017
Received in revised form 16 June 2017
Accepted 19 June 2017

Keywords:
Prototype corium of a nuclear reactor
Thermophysical properties
Melting crucible
Material carbonization
Uranium dioxide
Stainless steel

ABSTRACT

The paper is devoted to development and testing of a technology to manufacture the ingot of the prototype corium (resulted from out-of-pile conditions) of fast reactor followed by an experimental determination of the thermophysical properties (TP) (thermal diffusivity a, specific heat capacity C_p, and thermal conductivity λ) of such corium at the room temperature (298 K). The data on the thermo-physical properties of corium (melt of structural and fuel materials of the reactor core) will be used to calculate the temperature fields in the modeling the processes of keeping corium inside the power reactor vessel under the conditions of a severe accident.

1. Introduction

Currently, a great attention is paid to the problem of nuclear reactor safety operation (Alvarenga and Frutuoso, 2015; Fischer et al., 2014; Nguyen et al., 2008; Kang et al., 2014). It is generally agreed that occurrence of an accident accompanied by the fusion of core materials is a rare event. It can occur with a unique combination of circumstances, namely, with the simultaneous rejection of a large number of safety elements, and as a result the operation of cooling systems may break down and loss of the coolant may take place. In this case, the evolving heat of the fission reaction can lead to the destruction of the core geometry and its melting. To fully assess the risk of using reactors and increasing their safety, it is necessary to predict the possible course of an emergency situation, as well as to determine the possible consequences of severe accidents and measures to eliminate them.

As is known, the thermophysical properties of the corium (melt of structural and fuel materials of the reactor core), obtained in experiments simulating severe accidents at nuclear reactors, are extremely important information for identifying mechanisms of severe reactor accidents (Kaity et al., 2012; Skakov et al., 2015a, 2015b, 2017, 2016). That is why the experimental study of the thermophysical properties of the corium is necessary to construct a database that could be used in forecasting the course of severe accidents, and also in computational models.

For this purpose, the Institute of Atomic Energy of the National Nuclear Center of Kazakhstan (IAE NNC RK) has been intensively conducting experimental studies on the safety of light water and fast reactors under hypothetically possible severe accidents with melting of core materials. Important results in the study of thermophysical properties of prototype unirradiated corium of light water energy reactors have been obtained in experiments performed on out-of-pile stands of induction heating LAVA-B (Zhdanov et al., 2011) and VCG-135: technology to manufacture both the corium ingot on the stands LAVA-B and VCG-135 and the samples from obtained corium ingots as well as technologies to measure TP of these samples using experimental laboratory facility "UTFI-2" was developed and tested; the TP data of corium under room temperature was obtained;

* Corresponding author.
E-mail address: nur-advokat@mail.ru (N. Mukhamedov).

http://dx.doi.org/10.1016/j.nucengdes.2017.06.026
0029-5493/

the temperature dependences of the corium TP of various compositions were constructed.

Considering that experimental data on TP of corium of energy reactors has huge importance and required at modeling and forecasting the processes of severe accident of a reactor at nuclear power plants (NPP), since 2016 IAE NNC RK conducts similar studies of TP of a prototype corium of a fast reactor with sodium coolant using stand of induction heating VCG-135 and facility "UTFI-2" for determination of termophysical properties. In this connection the paper provides the first results that were obtained on the development and testing of the technology for manufacture of corium ingot using stand of high-temperature induction heating VCG-135, technology to manufacture samples from obtained corium ingot as well as to measure TP of these samples using facility for termophysical studies UTFI-2 under room temperature.

2. Manufacture of corium ingot and samples for TP measurements

When developing the technology for manufacturing a prototype corium of a fast reactor, it was considered that melting of the burden from the mixture of cladding tube (stainless steel) and fuel (uranium dioxide) core material of this reactor in graphite melting crucible will be carried out by high-frequency heating of the crucible inside water-cooled inductor windings in working chamber of the VCG-135 stand. Therefore the technology of manufacturing a prototype corium ingot will be closely related to the melting characteristics of the burden melting in graphite heated up to very high temperature (above the fusion temperature (T_{melt}) of UO_2, which is 2867 °C (Godin et al., 2008).

This feature is that the graphite material has the following significant disadvantage: during heating, it evaporates, and evaporation will more intense if the heating temperature is higher. In this connection, the burden materials in the graphite crucible will begin to carbonized long before the melting starts, and the composition of the resulting corium ingot will contain a significant amount of simple and complex carbides that should not be in the real corium.

It is obvious that in order to obtain a "pure" corium a barrier between the crucible and the melting materials should be created for their protection against carbonization. It should be noted that in the previously developed and tested technology for the manufacture of corium ingots of light water reactors (LWR) (Baklanov et al.), a thin (~50 μm) layer of zirconium carbide deposited on the inner surface of the crucible was used as a barrier, which allows obtaining a "pure" prototype corium of light water reactor at heating the crucible with a burden up to the temperature of 2600 °C.

The task of creating a protective barrier on the inner surface of a graphite crucible in the manufacture of a fast reactor corium ingot was solved by placing an insert from the tantalum carbide inside the crucible. The main points of this solving (Skakov et al.) were as follows. First, a glass from a sheet of tantalum of 0.8 mm thick using argon-arc welding was made, and then a crucible with an internal diameter equal to the outer diameter of the glass and a depth of the inner cavity equal to the height of the glass was grinded out from the porous graphite (porosity about 30%) and insert the tantalum glass into the cavity of the graphite crucible.

Then a glass was filled with foam graphite and the crucible was closed with a graphite cover, which has a through-hole in the center for viewing with a pyrometer. The assembly prepared by this means (Fig. 1) was thermally insulated with graphite felt and placed inside the inductor of VCG-135 stand (Fig. 2) to perform degassing and carbonization annealing.

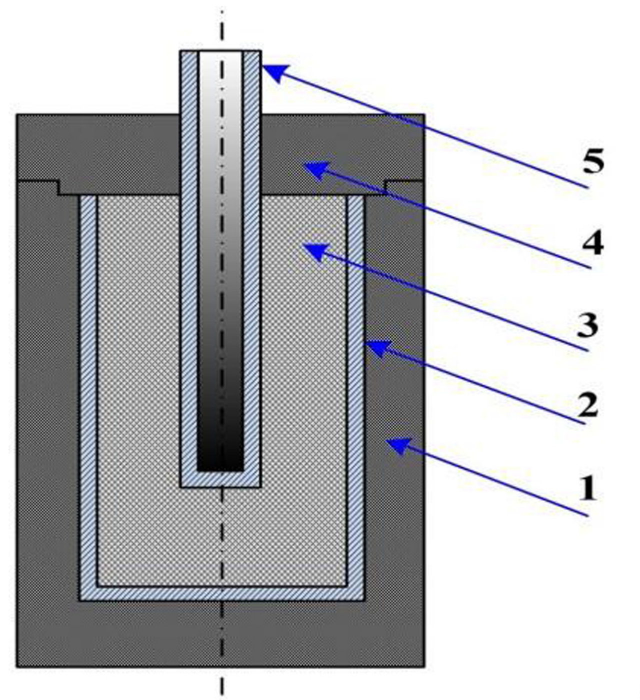

Fig. 1. Scheme of preparing the assembly of the melting unit for annealing: 1 – graphite crucible; 2 – tantalum glass; 3 – foam graphite; 4 – crucible cover; 5 – tantalum casing of thermometry system.

The degassing annealing of the assembly is carried out at a temperature of 800 °C in a vacuum with a residual pressure of 0.1 kPa for 30 min, and carbonization annealing is performed in helium at a pressure of 0.13 MPa in two steps: first at a temperature of 2500 °C for 60 min, and then at a temperature of about 2900 °C for 10 min. The temperature of 2500 °C in the first stage of carbonization annealing (where the process of tantalum carbonization begins and ends – the process of transition of tantalum to tantalum carbide by the mechanism of reactive diffusion of carbon into metal) is selected taking into account that it is below the T_{melt} of $Ta\text{-}Ta_2C$ eutectic that is equal to 2830 °C in accordance with the state diagram of the tantalum-carbon system (Hackett et al., 2009), which is shown in Fig. 3.

The annealing time at this stage was chosen on the basis of the results of test experiments, from which it followed that after a one-hour annealing, the average mass composition of carbidized tantalum, according to X-ray diffraction analysis, is close to $TaC_{0.9}$. Precisely this composition of the pre-stoichiometric tantalum carbide has a maximum T_{melt} for the entire homogeneity area of this compound (Fig. 3).

The temperature of 2900 °C in the second stage of carbonization annealing (where basically only the alignment of the carbide composition along the cross-section of the wall of the carbidized article takes place within 10 min) has been selected to control the achieved carbonization effect: the absence of melting of the carbided glass at this temperature will mean the use of a graphite crucible with a protective glass inside, to make an ingot of prototype corium by melting the burden at temperatures of about 3000 °C.

Using this technology to create a protective barrier, crucibles with TaC inserts were made to perform an experiment on manufacturing an ingot of a prototype corium (a 10-min carbonization annealing of these crucibles at a temperature of 2900 °C showed a perfectly acceptable state of the protective layer in the crucible). The ingot of the prototype corium was manufactured at the VCG-135 stand in one of the graphite melting crucibles with a protective insert (Fig. 4a). The burden loaded into this crucible (Fig. 4b)