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MODELING THE PROCESS OF DECAY HEAT IMITATION IN THE CORIUM AT THE «LAVA-B» FACILITY

It is known that corium is produced during the development of a severe accident at a nuclear power plant from a melt of core materials [1]. An important feature of the corium formed in an operating reactor is the presence of decay heat. Thus, it is especially important to take into account the presence of decay heat when conducting calculations and physical experiments, since it influences significantly on the nature of interaction between corium melt and structure materials of a reactor facility. For that reason, methods of decay heat simulation are subject to quite serious requirements to the depth and intensity of energy release in the corium when conducting different experiments.

This article considers induction and plasmatron heating technologies as methods to simulate decay heat in corium at the Lava-B facility. Characteristics of the selected methods of heating the corium prototype was analyzed by means of computer modeling. As a result of the work, parameters of melt heating using each of the considered methods were determined, and they were also cmpared. The used thermophysical models were created in the widely known ANSYS software based on the experimental section, which was used in one of the experiments at the Lava-B facility [2]. The main parameters of the corium-heater system were obtained by computer modeling for each of the considered methods and limits of their applicability for simulation of decay heat were determined when conducting the experiments at the facility.

Key words: corium, inductor, plasmatron, decay heat, Lava-B facility, ANSYS, non-stationary calculation

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«Лава-Б» қондырғысында кориумдағы қалдық энергия бөлу процесін модельдеу

Белгілі болғандай, атом электр станциясындағы ауыр апаттың даму процесінде кориумның пайда болуы жүреді – белсенді аймақ материалдарының балқуы [1]. Белсенді реакторда пайда болатын кориумның маңызды ерекшелігі - қалдық энергияның болуы. Осылайша, есептік зерттеулер мен физикалық эксперименттер жүргізу кезінде қалдық энергия бөлінуінің болуын ескеру маңызды, өйткені ол кориум балқымасының реакторлық қондырғының конструкциялық материалдарымен өзара іс-қимылының сипатына елеулі үлес қосады. Осы себепті, кориум прототипіндегі қалдық энергияны бөлуді модельдеу әдістеріне көлемді үлестірудің біркелкілігіне де, оның қарқындылығына да қатысты айтарлықтай талаптар қойылады.

Ұсынылған мақалада «Лава-Б» қондырғысына қатысты кориумдағы қалдық энергия бөлуді модельдеудің индукциялық және плазмалық әдістері қарастырылған. Кориум прототипін жылытудың таңдалған әдістерінің сипаттамаларын талдау компьютерлік модельдеу арқылы жүргізілді. Жүргізілген жұмыс нәтижесінде қарастырылған әдістердің әрқайсысы балқыманың қыздыру параметрлерін анықтады, сонымен қатар оларды салыстыру жүргізілді. Қолданылатын термофизикалық модельдер бұрын «Лава-Б» қондырғысындағы эксперименттердің бірінде қолданылған эксперименттік секция негізінде кеңінен танымал ANSYS бағдарламалық кешенінде жасалды [2]. Компьютерлік модельдеу әдісімен таңдалған әдістердің әрқайсысы үшін корий-жылытқыш жүйесінің негізгі параметрлері алынды және қондырғыда эксперимент жүргізу кезінде қалдық энергия бөлуді имитациялау үшін олардың қолданылу шекаралары анықталды.

Түйін сөздер: кориум, индуктор, плазмотрон, қалдық энергия бөлу, «Лава-Б» қондырғысы, ANSYS, стационарлық емес есептеу

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Моделирование процесса остаточного энерговыделения в кориуме на установке «Лава -Б»

Известно, что в процессе развития тяжелой аварии на АЭС происходит образование кориума – расплава материалов активной зоны [1]. Важной особенностью кориума, формирующегося в действующем реакторе, является наличие остаточного энерговыделения. Таким образом, учитывать наличие остаточного энерговыделения немаловажно при проведении расчетных исследований и физических экспериментов поскольку оно вносит ощутимый вклад в характер взаимодействия расплава кориума с конструкционными материалами реакторной установки. По этой причине к методам имитации остаточного энерговыделения в прототипе кориума предъявляются достаточно серьезные требования, которые касаются, как равномерности объемного распределения, так и его интенсивности.

В представленной статье рассмотрены индукционный и плазмотронный методы имитации остаточного энерговыделения в кориуме применительно к установке «Лава-Б». Анализ характеристик выбранных методов нагрева прототипа кориума выполнялся посредством компьютерного моделирования. В результате проведенной работы определены параметры нагрева расплава каждым из рассматриваемых методов, а также произведено их сравнение. Применяемые теплофизические модели были созданы в широко известном программном комплексе ANSYS на основе экспериментальной секции, которая применялась ранее в одном из экспериментов на установке «Лава-Б» [2]. Способом компьютерного моделирования получены основные параметры системы кориум-нагреватель для каждого из выбранных методов и определены границы их применимости для имитации остаточного энерговыделения при проведении эксперимента на установке.

Ключевые слова: кориум, индуктор, плазмотрон, остаточное энерговыделение, установка «Лава-Б», ANSYS, нестационарный расчет

Introduction

The most severe accidents of nuclear power plant reactors are accompanied by core melting and corium formation. Corium is a melt with a radioactive mixture of uranium oxide, zirconium, zirconium oxides and steel components (products of high-temperature interaction of metals with an oxidizing environment) and other structural elements. The escape of corium, under certain conditions, beyond the borders of the reactor plant is a very real scenario due to a large amount of stored energy and the presence of decay heat in the corium. That is, nuclear fuel contained in the corium melt continues to be a source of heat releasing due to the decay of ^{235}U nuclear fission fragments accumulated during the operation of the reactor. This allows the corium to remain in a liquid state for a long time and melt the reactor construction with its subsequent escape to the surface of the ground and even groundwater.

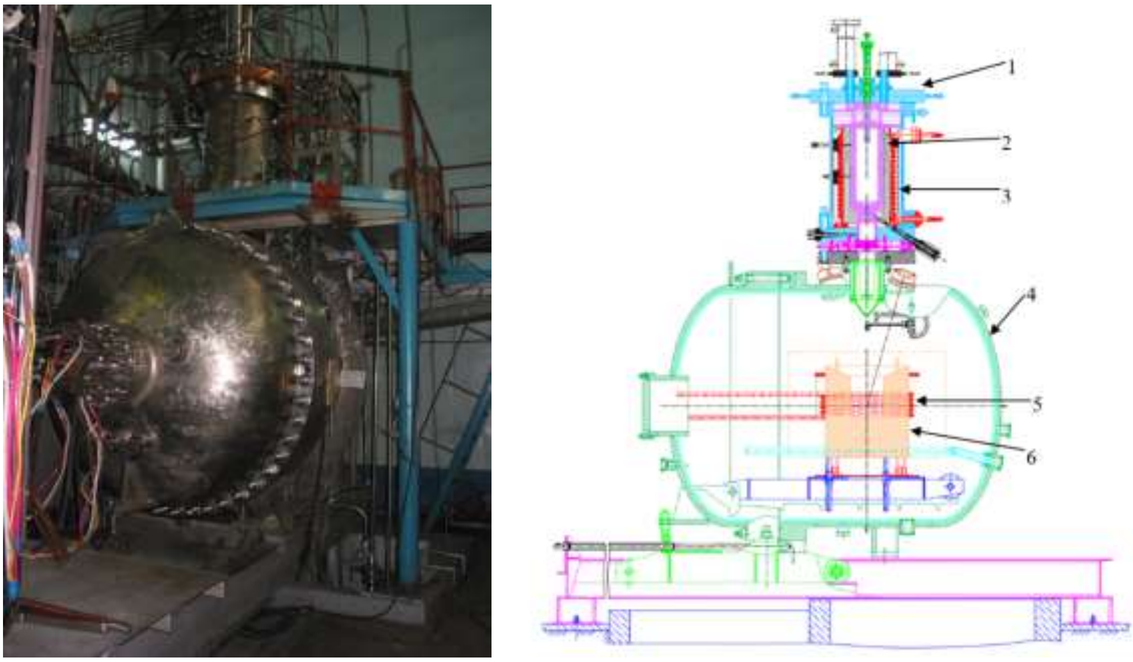
Obviously, it is necessary to conduct experimental studies on the interaction of corium with the structural elements of the reactor plant in order to prevent such a scenario of the development of a severe accident at a nuclear power plant. For example, such experiments are in demand in studies of in-vessel and ex-vessel corium retention. They were and are being conducted as part of concept to design and establish severe accident management systems by cooling, controlled movement and localization of the core melt, both inside the reactor vessel and outside it [3].

In such experiments on the physical modeling of processes occurring during severe accidents, a corium imitator is used, which called "prototype corium". The prototype of corium is a replacement for real corium. Its characteristics are close to real corium in most parameters, but do not create a dose load on people (*hereinafter as corium is understood a "prototype of corium"*). Therefore, the essential difference between the prototype and the real corium is that the first one is not a source of heat. That is, there is no self-sustaining radioactive decay in the prototype corium [4].

To ensure modeling conditions that are as close as possible to natural ones, it is necessary to take into account not only the compliance of prototype corium composition to real one, but also the energy release in the melt within a given level. Thus, the device that provides the energy release in the corium must imitate the fission reaction both in magnitude and in the nature of its distribution in the volume of the corium.

Several experimental facilities have been created in the world where such studies can be conducted, however, they differ not only in design, but also in the methods used to imitate decay heat [5-10].

Among the mentioned experimental complexes allowing for various studies of the final stage of a severe accident with the melting of the core, the LAVA-B facility is considered (Fig.1). Experimental facility is designed to solve a wide range of tasks with a corium and operated by the "Institute of Atomic Energy" branch of the National Nuclear Center of the Republic of Kazakhstan [11]. The Lava-B facility includes two main functional units: an electric melting furnace for the preparation of corium melt and a melt receiver, where concrete vessel for experimental study is placed. The facility allows melting up to 60 kg of a prototype mixture of LWR core materials by induction melting in a “hot crucible” followed by pouring the melt into the experimental section.



1– EMF (electric melting furnace), 2 – graphite crucible, 3 – EMF inductor, 4 – MR (melt receiver), 5 – MR inductor, 6 – concrete trap.

Figure 1 – Outer view and scheme of “Lava-B” facility

Currently, several research works were conducted at the «Lava-B» facility under various programs. They are connected with experiments to study the interaction of corium with structural elements of a nuclear reactor, reactor vessel, containment building, as well as with the sacrificial materials of core catcher of an NPP [12-14].

Depending on the object and goals of study, both induction and plasmatron heating of the corium are applied in the experimental section of the Lava-B facility as a method of imitate decay heat [15-16]. In order to ensure required quality of the conducting researches, it is necessary to study the heating of the corium melt in an experimental section by methods using at the “Lava-B” facility as well as to compare them to justify the most optimal method for decay heat imitation during physical modeling of the situation of an ex- vessel severe accident at a nuclear power plant.

The most effective way that allows to consider two methods of decay heat imitation with minimal costs is the computer modeling method. Computer modeling of thermophysical processes of melt heating in the experimental section allows:

1) preliminarily estimating the temperature fields established during the interaction of the corium melt with various substances under a given heating device mode in order to prevent heating of the elements of the experimental section above the allowable temperatures;

2) estimate the characteristics of the heating device required to establish a certain temperature field in a particular experiment;

3) analyze the thermophysical processes

occurring in the experimental section based on a comparison of the results of computer modeling and experimental data.

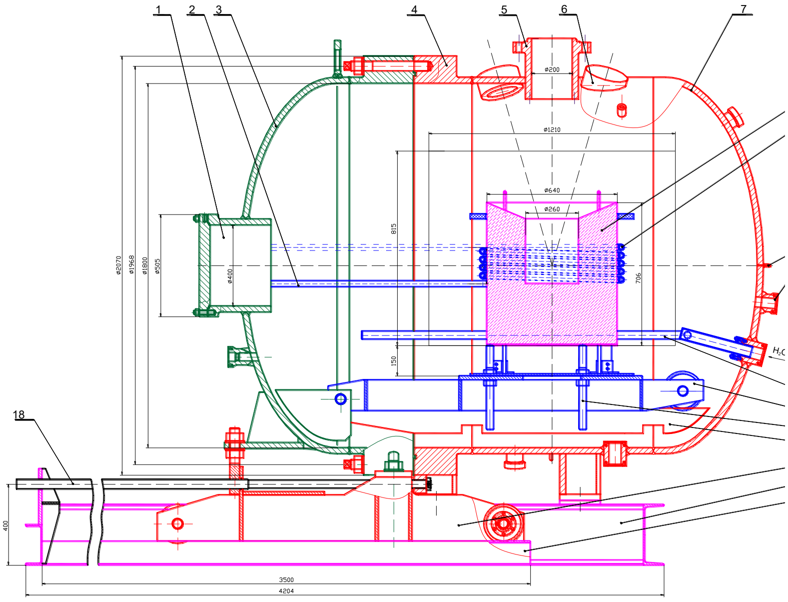
Thus, in this article, the induction and plasmatron heating methods are considered by computer modeling method in order to obtain the parameters of the melt-heater system. The advantages and disadvantages of each melt heating method are determined as well as the limits of their applicability were determined for decay heat simulation during the experiments on the “Lava-B” facility.

Object statement of decay heat modeling

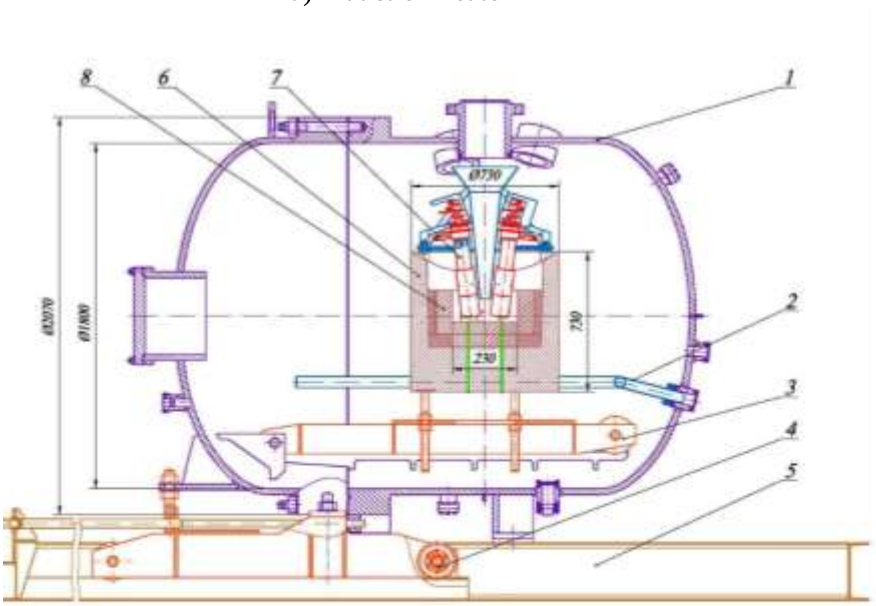
The objective of this work is choosing a decay heat simulation method for physical modeling of a severe accident at a nuclear power plant using the “Lava-B” facility.

To achieve this goal, in this article, an experimental situation is simulated when the melt of the corium prototype is poured into a special melt trap for its interaction with various materials. Calculations of the thermal state of the thermophysical model were performed using the ANSYS software [17].

Figure 2 shows the schematic diagrams of the experimental section of the “Lava-B” facility with an induction and plasmatron heaters [18].



a) induction heater



b) plasmatron heaters

Figure 2 – Schematic diagram of the “Lava-B” facility with induction and plasmatron heaters

The thermophysical model for calculations was created based on the scheme of a special experimental melt trap (Fig.3) which was used in the one of experiments at the "Lava-B" facility. Induction heater was used as a method of decay heat simulation. As for the thermophysical model of plasmatron heating, it was created similarly to the model with induction heating of the melt. However, there are little changes in the scheme, taking into account the presence of plasmatron heaters.

Due to the symmetry of the trap relatively to the central axis, for modeling heat transfer in the melt trap, the following were created:

- Two-dimensional axisymmetric computational domain of thermophysical model of induction heating of melt in the trap;
- The fourth part of a three-dimensional axisymmetric computational domain of thermophysical model of plasmatron heating of melt in the trap.

Computational domains of thermophysical models of traps are presented in Figure 4.

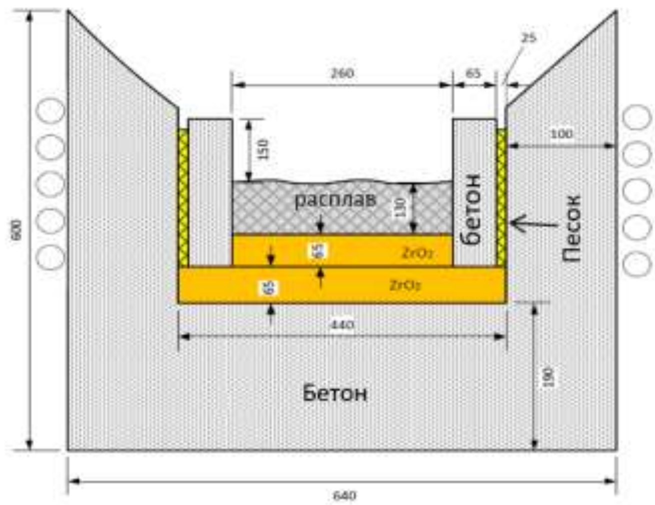
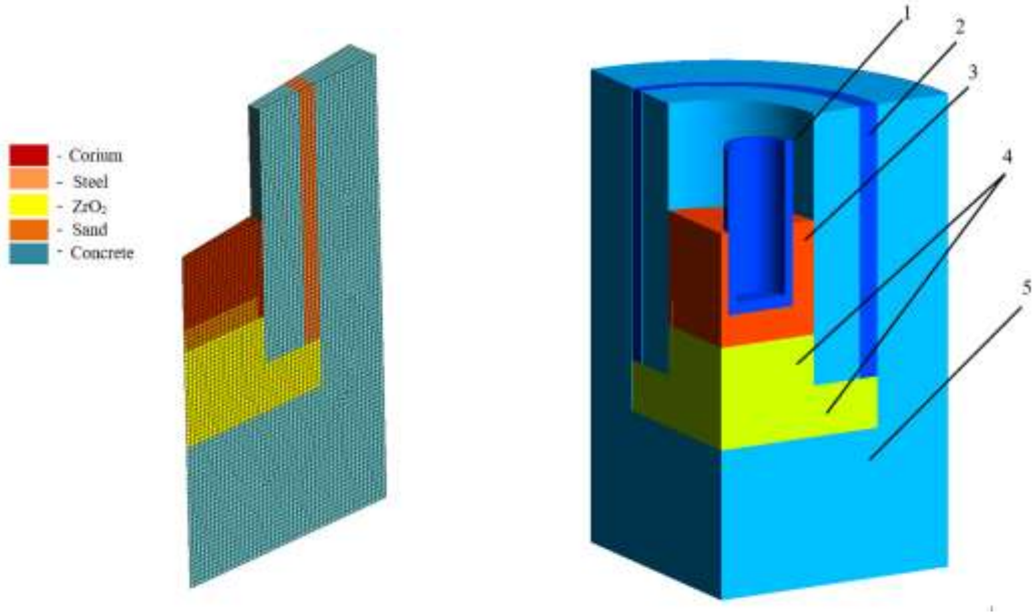


Figure 3 – Scheme of the experimental melt trap of the "Lava-B" facility



a) Induction heating b) plasmatron heating
1 – plasmatron; 2 – sand; 3 – corium; 4 – ZrO_2; 5 – concrete

Figure 5 – Computational domains of thermophysical models of traps

To compare the two melt heating methods in each of the calculations are equivalent:

- Initial conditions (initial corium temperature 2500 °C);
- Mass of corium;
- Thermophysical properties of materials;
- The power released in the melt for both types of melt heating (the power released in the melt was 35 kW);
- The estimated heating time is 30 minutes.

The heat release in the melt was set depending on the features of induction and plasmatron heating:

1) The surface effect of penetration deep into the materials of the electromagnetic field of the inductor or the skin effect (in this calculation, 70% of the total heat was released on the surface layer). The depth of this surface layer is determined by the theory of induction facilities [19].

2) In the case of the plasmatron method, an approach was used according to which the heat transferred to the corium is set on the internal surface of the graphite tip of plasmatrons in the area of electric arc formation. This simplification allows to accelerate and simplify the calculations significantly courtesy of reducing the number of elements in the thermophysical model. Thus, in this case only the presence an external surface of graphite as a source of heat in the model is sufficient.

Validation of the described methods for modeling decay heat in the corium was conducted earlier and, therefore, they can be used for non-stationary calculations of temperature changes in trap elements [20-21].

The thermophysical models take into account:

- The dependence of the properties of the trap elements on temperature;
- Heat exchange by radiation;
- Convective heat exchange between the external surfaces of the model and the environment.

Some properties of corium during computer modeling were used according to literary sources [22-23]. It should be noted that due to shortages of data about dependence of the coefficient of thermal conductivity of corium on temperature, its value was set as a constant. The value of the thermal conductivity coefficient was set similarly to the previously performed calculations of corium heating in the ISTC project No. K-1265 under the INVECOR program [24-25].

The thermophysical properties of the trap elements were used according to the literary source [26].

Results of computer modeling of decay heat in the corium at the "Lava-B" facility

Figure 5 shows results of calculating the heating of the corium in the melt trap by the induction method.

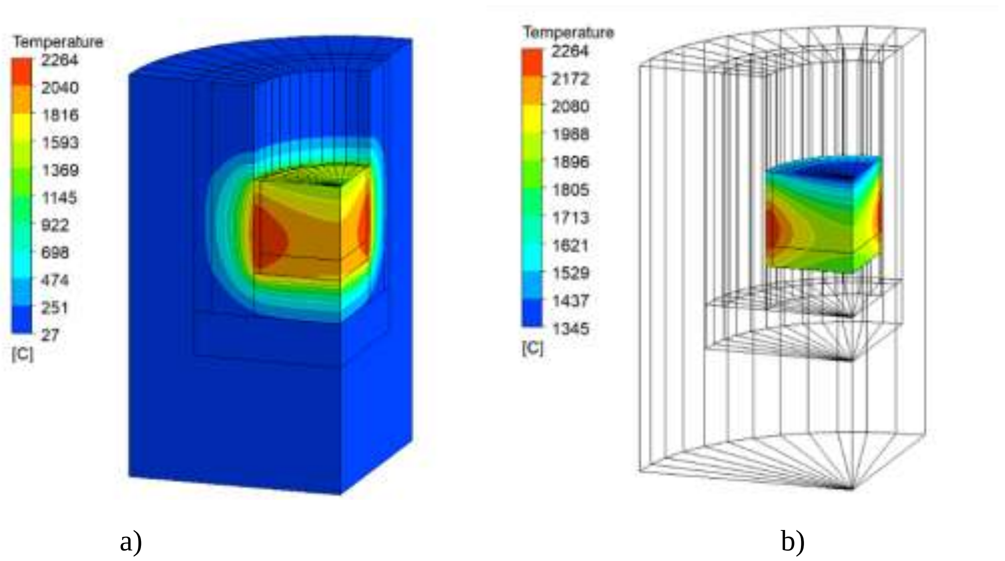
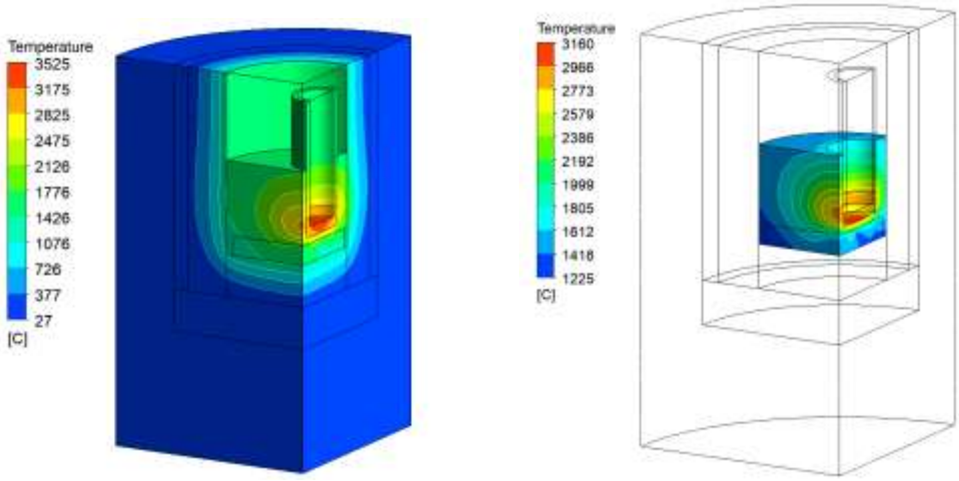


Figure 5 – Temperature distribution of the model during induction heating

Throughout the calculation, heat is released on the side surface of the corium melt. Heat is transferred from the area of heat release to the central volumes of the corium due to heat conduction. Figure 5b shows that the minimum temperatures in corium are observed on the surface of the melt. This can be explained by radiation from the surface of corium, as well as by convective heat exchange with the environment.

Figure 6 shows results of calculating the heating of the corium in the melt trap by the plasmatron method.



a) b)

Figure 6 – Temperature distribution of the model during plasmatron heating

Figure 6 shows that the distribution of heat in the corium during plasmatron method occurs from the heat-generating area of the heater to the side surfaces. Minimum temperatures are observed in the corium-wall boundary area. Obviously, this is due to the remoteness of the heat release area and the active heat exchange process between the trap materials and the corium. It leads to a significant decrease in the temperature of the corium in that area.

Table 1 shows the calculated values of corium temperatures obtained during computer modeling.

Table 1. Calculated corium temperature

Parameter	**Induction heating**	**Plasmatron heating**
Average temperature of corium, °C	2009	2193
Maximum corium temperature, °C	2264	3160
Minimum corium temperature, °C	1345	1225

As shown in Table 1, when using plasmatron heating, the maximum corium achieved temperature is significantly higher compared to the induction heating method. The advantage of plasmatron heating is also seen in the case of comparing the average volume temperatures of corium. According to table 1, it can be argued about the advantage of the plasmatron method of decay heat imitation over induction.

Plasmatron heaters are based on the method of indirect electric arc heating [27]. In the construction of the plasmatron heaters used in the "Lava-B" facility, an electric arc is formed, the temperature of which can reach several thousand degrees. The heat from the electric arc is transferred through a special protective graphite tip to the corium melt. Thus, considering the high temperature that arises in the plasmatron heater, high temperatures comparable to the temperature inside the heaters will be observed in the area of their contact with the corium melt.

The presence of a small area of corium heated to higher temperatures compared to the rest of corium areas leads to an increase in the average temperature of the entire corium. In this regard, the data in Table 1 don't allow an objective comparison of the two heating methods.

When comparing the temperature fields of two thermophysical models (Fig.5b and Fig.6b), it is seen that with induction heating, corium heating is more uniform due to volumetric heat release of energy. This is confirmed if we look at the graph of the temperature distribution in a random section (from the center to the periphery) in the corium, shown in Figure 7. The temperature distribution during induction heating is more uniform. At the same time, when using plasmatron heating a large temperature gradient is observed.

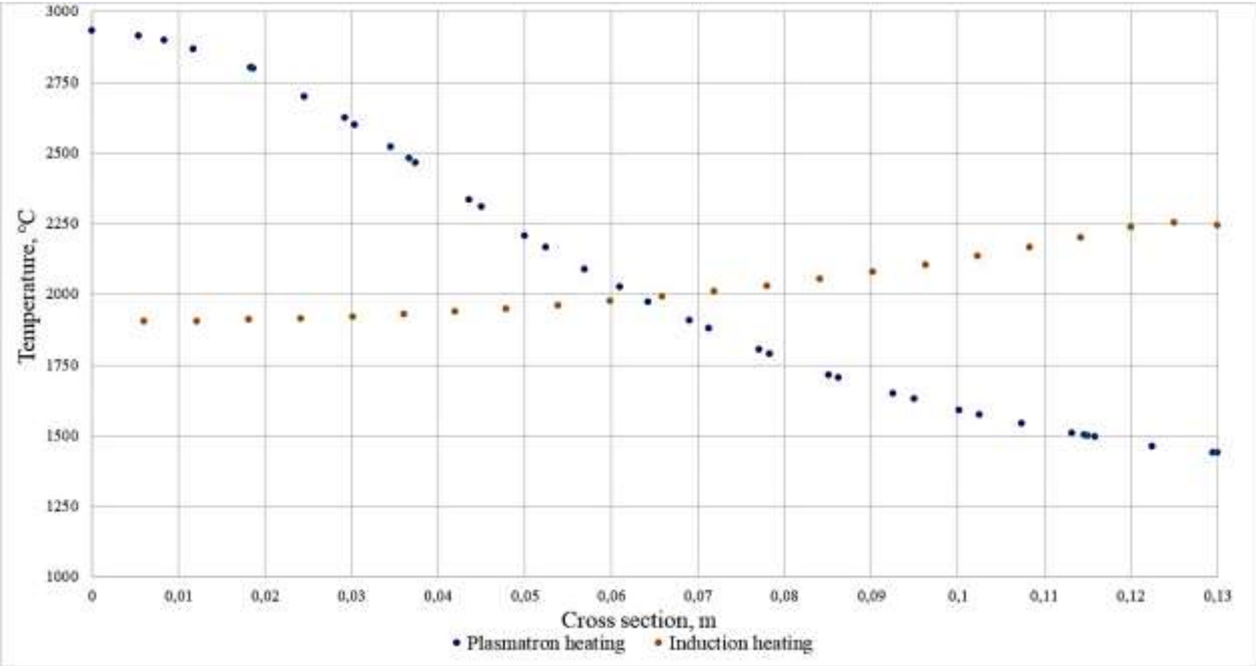


Figure 7 – Temperature distribution in the melt

Conclusion

Modeling of decay heat imitation at the "Lava-B" facility by induction and plasmatron heating methods was performed using ANSYS software. The calculation was performed under the same initial conditions to compare these methods. The objective of calculation was to choose the most optimal method of decay heat simulation for the studying the processes of a ex-vessel accident at NPP when localization corium in the core cathcer.

Numerical calculations have shown that higher corium temperatures can be achieved when using plasmatron heaters compared to an induction heater. This feature of plasmatron heaters can be used when conducting experiments with corium, especially in cases where it is impossible to use an induction heater. For example, in experiments with the study of the interaction of corium with materials that can be heated by the action of the electromagnetic field of the inductor.

However, in the context of future experiments at the "Lava-B" facility [28], an induction heater is more more preferable method of decay heat imitation. In the case of induction heating, heat is released on the side surface of the corium within the skin layer. The volumetric release of energy by an induction heater allows to obtain a more uniform thermal field, and the release of energy in the area of constant heat exchange processes of corium with trap materials allows to maintain corium in a molten state. It allows bringing the experimental situation closer to real processes.

At the same time, a small heat-releasing surface of plasmatron heaters leads to the formation of a large temperature gradient in corium. Under certain conditions, solidification of corium is expected in the areas most remote from the heaters, especially in areas of intensive heat exchange of corium with trap materials. In this regard, it is necessary to use a complex system of heaters placed in various parts of the corium to achieve a uniform thermal field over the entire volume and heat pattern acceptable in symmetry.

As a result of the perfomed calculations, it can be concluded that with an equal amount of heat that the heaters transfer to the corium melt, induction heating is more effective from the point of view of its use as a method of decay heat imitation. Thus, induction heating should be considered as method of decay heat imitation when conducting experiments at the "Lava-B" facility for achieving quite uniform temperature field over the entire volume of corium and maintaining it in the molten state for time required for study interaction of corium and considered materials.

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References

1 Арутюнян Р.В. "Китайский синдром "// Природа. – 1990. – №11. – С. 35-41.

2 Maruyama Y., Tahara M., Nagasaka H., Kolodeshnikov A., Zhdanov V., Vassiliev Yu. Recent results of MCCI studies in COTELS project // NTHAS3: Third Korea-Japan Symposium on Nuclear Thermal Hydraulics and Safety. – Kyeongju, Korea. – 13-16 October 2002.

3 Васильев Ю.С., Вурим А.Д., Жданов В.С., Зуев В.А., Кенжин Е.А., Колодешников А.А., Пахниц А.В. Экспериментальные исследования по моделированию процессов характерных для тяжелых аварий ядерных реакторов проведенные в ИАЭ // Вестник НЯЦ РК. − 2009. − Вып. 4. − С.26-54.

4 Christophe Journeau Contribution des essais en matériaux prototypiques sur la plate-forme PLINIUS à l'étude des accidents graves de réacteurs nucléaires // Sciences de l'ingénieur [physics] // Université d'Orléans. – 2008. – 229 p.

5 Fink J. K., Thompson D. H., Spencer B. W., Sehgal B. R. Aerosol and melt chemistry in the ACE molten core-concrete interaction experiments // High Temperature and Materials Science. – 1995. – Vol.33(1). – P.51-76.

6 Journeau C., Piluso P., Haquet J.F., Boccaccio E., Saldo V., Bonnet J.M., Malaval S., Carénini L., Brissonneau L. Two-dimensional interaction of oxidic corium with concretes: The VULCANO VB test series // Annals of Nuclear Energy. – 2009. – Vol. 36. – P.1597-1613.

7 Foit, J. J. MCCI of a Metal and Oxide Melt with Reinforced Siliceous Concrete in MOCKA Experiments // 22nd International Conference on Nuclear Engineering (ICONE22). – Prague, Czech Republic. – 7-11 July 2014.

8 Farmer M.T., Kilsdonk D.J., and Aeschlimann R.W. Corium Coolability under Ex-Vessel Accident Conditions for LWRs // Nuclear Eng. Technology. – 2009. – Vol. 41. – P.575-602.

9 Miassoedov A., Cron T., Gaus-Liu X., Palagin A., Schmidt-Stiefel S., Wenz T. LIVE experiments on melt behavior in the reactor pressure vessel lower head // 8th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics. – Pointe Aux Piments, Mauritius. – 11 – 13 July 2011. – P.793-801.

10 Kim H.Y., An S.M., Jung J., Ha K.S., Song J.H. Corium melt researches at VESTA test facility // Nuclear Engineering and Technology. – 2017. – Vol. 49. – Issue 7. – P.1547-1554.

11 Nazarbayev N.A., Shkolnik V.S., Batyrbekov E.G. et al. Scientific, Technical and Engineering Work to Ensure the Safety of the Former Semipalatinsk Test Site. London. – 2017. – Vol.3. – P.290.

12 Kurita Tomohisa, Isao Sakaki, Fumiyo Sasaki, et al. Test and evaluation plan for passive debris cooling system // 9th International Conference NUCLEAR AND RADIATION PHYSICS. – 24-27 September 2013. – Almaty, Kazakhstan. – P.19-29.

13 Shohei Kawano, Takahiro Hayashi, Yasuo Morishima, et al. Characterization of fuel debris by large-scale simulated debris examination for Fukushima daiichi nuclear power station // Proceedings of ICAP 2017. – 24-28 April 2017. – Fukui and Kyoto (Japan). – P.1105-1110.

14 Назарбаев Н.А., Школьник В.С., Батырбеков Э.Г., Березин С.А., Лукашенко С.Н., Скаков М.К. Проведение комплекса научно-технических и инженерных работ по приведению бывшего Семипалатинского испытательного полигона в безопасное состояние. – т. III. – г. Курчатов. – 2016. – С.320-356.

15 Baklanov V., Zhdanov V et al. Experiments to justify structure of residual heat simulation assembly under INVECOR project // Bulletin of the National Nuclear Center of the Republic of Kazakhstan. – 2009. – Vol.1. – P.66 – 76.

16 Zhdanov V. COTELS Project (1): Overview of Project to study FCI and MCCI during a Severe Accident // OECD Workshop on Ex-Vessel Debris Coolability. – Karlsruhe, Germany. – 15-18 November 1999.

17 ANSYS Fluent Tutorial Guide, 2016.

18 Zhdanov V., Baklanov V., Bottomley P.W.D., Miassoedov A., Tromm T.W., Journeau Ch., Altstadt E., Clement B., Oriolo F. Study of the processes of corium-melt retention in the reactor pressure vessel (INVECOR) // Proceedings of ICAPP 2011. – Nice, France. – 2-5 May 2011. – P.1300-1308.

19 Иванова Л.И., Гробова Л.С., Сокунов Б.А., Сарапулов С.Ф. Индукционные тигельные печи: Учебное пособие. 2-е изд., перераб. и доп. // Екатеринбург: Изд-во УГТУ – УПИ. – 2002. – 87 с.

20 Толеубеков К.О., Хажидинов А.С., Акаев А.С. Моделирование индукционного нагрева при имитации остаточного энерговыделения в кориуме при взаимодействии с жаропрочными материалами //Вестник НЯЦ РК. – 2021. – Вып.1. – С.9-14.

21 Рамазанова К.М., Зуев В.А., Гановичев Д.А., Хажидинов А.С., Акаев А. С. Расчет температурного поля кориума и огнеупорных блоков ловушки расплава установки «Лава-Б» // Вестник НЯЦ РК. – 2016. – Вып. 3. – С.134-139.

22 В. Г. Асмолов, В. Н. Загрязкин, Е. В. Астахова, В. Ю. Вишневский, Е. К. Дьяков, А. Ю. Котов, В. М. Репников Плотность UO2–ZrO2-расплавов // ТВТ. – 2003. – Том 41, вып. 5. – С.714-719.

23 И.В. Позняк, А.Н. Шатунов, А.Ю. Печенков Измерение электропроводности расплава кориума //Известия СПбГЭТУ «ЛЭТИ». – 2008. – Вып.10. – С.39-45.

24 https://istc.int/ru/project/DA8802253C138C29C3257052005303CFICTS project #K-1265 INVECOR (IN-VEssel Corium Retention in accident of water reactor) [Электронный ресурс].

25 https://portal.tpu.ru/portal/pls/portal/!app_ds.ds_view_bknd.download_doc?fileid=4000 Бакланов В.В. Приборно-измерительный комплекс для исследования взаимодействия материалов ядерного реактора при

тяжелых авариях: диссертация на соискание учёной степени кандидата технических наук, Юргинский технологический институт ТПУ, Югра, 2016 // [Электронный ресурс].

26 Чиркин В.С Теплофизические свойства материалов ядерной техники. – М.: Атомиздат, 1968.

27 Жуков М.Ф. Электродуговые нагреватели газа (плазмотроны). – М.: Наука, 1973. — 232 с.

28 Bekmuldin M.K., Skakov M.K., Baklanov V.V., Gradoboyev A.V., Akaev A.S. Heat-resistant composite coating with a fluidized bed of the under-reactor melt trap of a light-water nuclear reactor // Eurasian Physical Technical Journal. – 2021. – Vol.18(3). – P. 65-70.

References

1 R.V. Arutyunyan, Nature, 11, 35-41 (1990). (in Russ).

2 Y. Maruyama et al., NTHAS3: Third Korea-Japan Symposium on Nuclear Thermal Hydraulics and Safety (Kyeongju, 13-16 October, 2002).

3 Yu.S. Vasiliev, A.D. Vurim, V.S. Zhdanov, V.A. Zuyev, Ye.A. Kenzhin and A.A. Kolodeshnikov, NNC RK Bulletin, 4, 26-54 (2009). (in Russ).

4 J. Christophe, Contribution des essais en matériaux prototypiques sur la plate-forme PLINIUS à l'étude des accidents graves de réacteurs nucléaires, (Université d'Orléans, 2008), 229 p.

5 J. K. Fink, D. H. Thompson, B. W. Spencer and B. R. Sehgal, High Temperature and Materials Science, 33(1), 51-76 (1995).

6 C. Journeau, P. Piluso, J.F. Haquet, E. Boccaccio, V. Saldo, J.M. Bonnet, S. Malaval, L. Carénini and L. Brissonneau, Annals of Nuclear Energy, 36, 1597-1613 (2009).

7 J.J. Foit, 22nd Int. Conf. on Nuclear Engineering (ICONE22), (Prague, 7-11 July, 2014).

8 M.T. Farmer, D.J. Kilsdonk and R W. Aeschlimann, Nuclear Eng. Technology, 41, 575-602, (2009).

A. Miassoedov et al., 8th Int. Conf. on Heat Transfer, Fluid Mechanics and Thermodynamics (Pointe Aux Piments, 11 – 13 July, 2011), p.793-801.

9 H.Y. Kim, S.M. An, J. Jung, K.S. Ha and J.H. Song, Nuclear Engineering and Technology, 49(7), 1547-1554 (2017).

10 N.A. Nazarbayev, V.S. Shkolnik, E.G. Batyrbekov and et al., Scientific, Technical and Engineering Work to Ensure the Safety of the Former Semipalatinsk Test Site Vol.3, (London, 2017), p.290.

11 T. Kurita et al., 9th Int. Conf. Nuclear and Radiation Physics (Almaty, 24-27 September, 2013), p.19-29.

12 Sh. Kawano et al., Proc. of ICAP 2017 (Fukui and Kyoto, 24-28 April, 2017), p.1105-1110.

13 N.A. Nazarbayev, V.S. Shkolnik, E.G. Batyrbekov and et al., Scientific, Technical and Engineering Work to Ensure the Safety of the Former Semipalatinsk Vol.3, (Kurchatov, 2016), p. 320-356. (in Russ).

14 V.V. Baklanov, V.S. Zhdanov, Ye.V. Malysheva, I.M. Kukushkin, V.I. Ignashev, M.I. Kukushkin, A.V. Mikisha and V.V. Zverev, NNC RK Bulletin, 1, 66-76, (2009). (in Russ).

15 V. Zhdanov, OECD Workshop on Ex-Vessel Debris Coolability (Karlsruhe, 15-18 November, 1999), 8 p.

16 ANSYS Fluent Tutorial Guide (Southpointe, 2013), 1034 p.

17 V. Zhdanov et al., Proc. of ICAPP 2011 (Nice, 2-5 May, 2011), pp.1300-1308.

18 L.I. Ivanova, L.S. Grobova, B.A. Sokunov, S.F. Sarapulov, Induction crucible furnaces (Yekaterinburg: USTU, 2002), 87 p. (in Russ).

19 K.O. Toleubekov, A.S. Khazhidinov and A.S. Akaev, NNC RK Bulletin, 1, 9-14 (2021). (in Russ).

20 K.M. Ramazanova, V.A. Zuev, D.A. Ganovichev, A.S. Khazhidinov and A.S. Akayev, NNC RK Bulletin, 3, 134-139 (2016). (in Russ).

21 V.G. Asmolov, V.N. Zagryazkin, E.V. Astakhova, V.Yu. Vishnevsky, E.K. Dyakov, A.Yu. Kotov and V.M. Repnikov, High Temperature, 41(5), 714-719 (2003). (in Russ).

22 I.V. Poznyak, A.N. Shatunov and A.Y. Pechenkov, Proceedings of Saint Petersburg Electrotechnical University, 10, 39-45 (2008). (in Russ).

23 https://istc.int/ru/project/DA8802253C138C29C3257052005303CF «ICTS project #K-1265 INVECOR»,

24 V.V. Baklanov, Dissertation for the degree of Candidate of Technical Sciences, Yurga, 2016, 173 p. (in Russ).

25 V. Chirkin, Thermophysical properties of materials of nuclear engineering (Moscow: Atomizdat, 1968), 356 p. (in Russ).

26 M.F. Zhukov Electric arc gas heaters (plasmatrons) (Moscow: Nauka, 1973), 232 p. (in Russ).

27 M.K. Bekmuldin, M.K. Skakov, V.V. Baklanov, A.V. Gradoboyev and A.S. Akaev, Eurasian Physical Technical Journal, 18(3), 65-70 (2021).