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Original Article

Unsteady heat exchange at the dry spent nuclear fuel storage

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ABSTRACT

Unsteady thermal processes in storage containers with spent nuclear fuel were modeled. The daily fluctuations of outer ambient temperatures were taken into account. The modeling approach, which is based on the solving of conjugate and inverse heat transfer problems, was verified by comparison of measured and calculated temperatures in outer channels. The time delays in the reaching of maximal temperatures for each spent fuel assembly were calculated. Results of numerical investigations show that daily fluctuation of outer temperatures does not have a large influence on the maximal temperatures of stored spent fuel, so that fluctuation can be neglected and only daily average temperature should be considered for safety estimation using the "best estimation" approach.

1. Introduction

The dry storage of spent nuclear fuel (SNF) is widespread. According to International Atomic Energy Agency data [1,2], today 73% of operated storage facilities are of dry type. All of them require good understanding of the real processes that take place during their operation. Thermal calculations play key roles in safety estimation using the conservative approach [3,4] or the "best estimation" method [5,6].

Depending on the type of organization, all dry storage facilities can be divided into two types: the first are placed inside buildings and the second are placed on open sites. Closed storage facilities do not require permanent control of the outer temperatures because outer air does not have a direct influence on the thermal state of containers inside buildings. The storage buildings can contain their own central cooling systems; otherwise, the temperature inside the buildings is usually stable and does not have daily temperature fluctuations. Another situation takes place with open storage facilities. Temperature of atmospheric air plays a key role in SNF cooling. Therefore, it is extremely important to know how external temperature fluctuations influence the temperature of the SNF inside storage containers.

Usually, researchers consider unsteady heat transfer problems, which are related to nuclear fuel inside reactors [7,8]. Unfortunately, they have not paid enough attention to the thermal "behavior" of spent nuclear fuel during all periods of storage (especially for ventilated containers) in large storage facilities. There are some papers related to thermal investigations for the back end of the nuclear fuel cycle [9,10], but they have certain specific details (e.g., describing an underground repository or having a short period of transportation) and cannot be related to interim dry spent nuclear fuel storage. Some authors in this topic consider the thermal problem through quasi-steady formulation [11,12], but this approach does not sufficiently explain the transient thermal state of SNF and the results, which are finally used in safety analysis, do not take into account the unsteady thermal behavior of the storage components. Another approach is direct unsteady thermal simulation (approach based on computational fluid dynamics methods) of components of storage casks [10], or modeling of casks under special storage conditions [13,14], or modeling nonventilating casks [15]. Unfortunately, these results cannot be used for effective thermal analysis of dry storage facilities with ventilated containers, which are the type of container used in many countries.

The main goal of this study is to detect the influence of changes in external temperatures on the thermal state of SNF inside storage containers; this can be very important in the "best estimation" approach to safety analysis and during the development of safety measures.

2. Problem formulation

One of the biggest facilities in Europe is the Dry Spent Nuclear Fuel Storage Facility (DSNFSF), operated by Zaporizhska NPP

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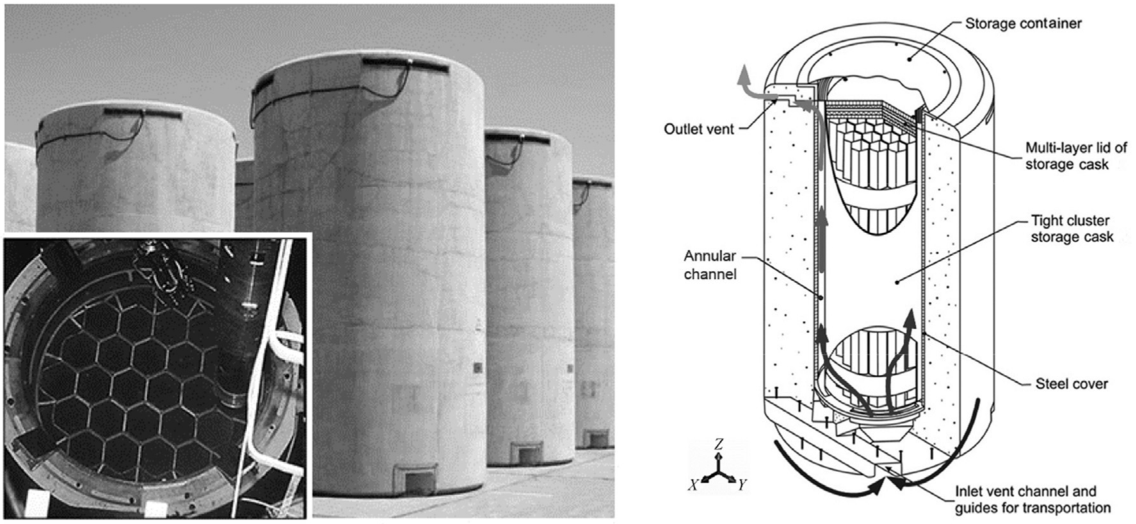

Fig. 1. Container for dry storage.

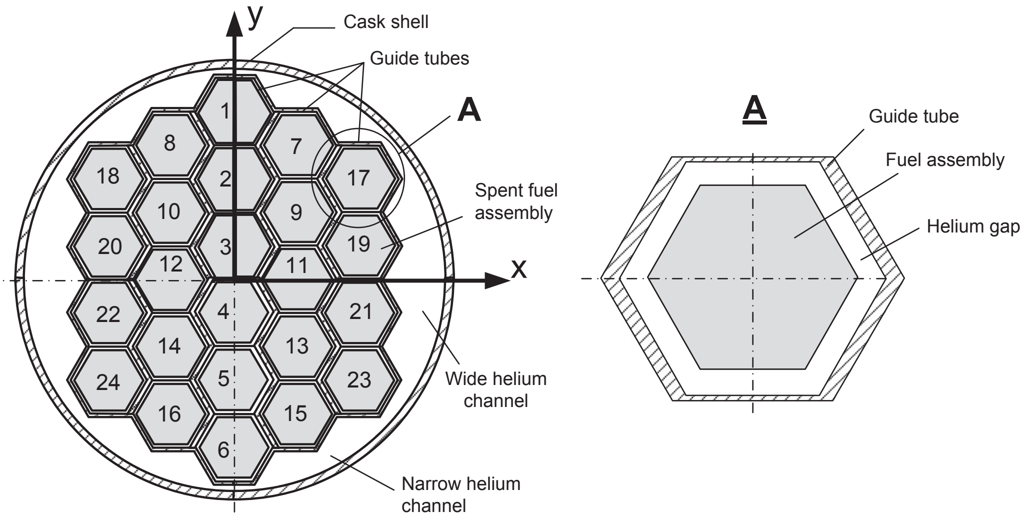

Fig. 2. Structure of storage cask (horizontal section). A, part view of spent fuel assembly inside guide tube.

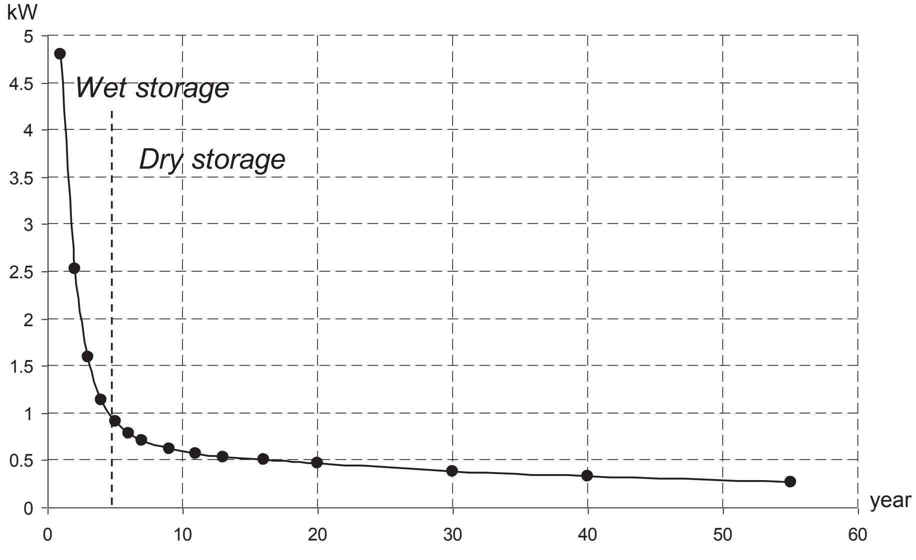

Fig. 3. Decay heat of fuel assembly.

(Ukraine). This facility was designed for storage of more than 9000 spent fuel assemblies (SFAs) from WWER-1000 reactors. The DSNFSF is an open storage platform, so storage containers are under the influence of weather factors (insolation, precipitation, wind, and seasonal and daily temperature fluctuations) [16]. In this study, the influence of the daily temperature fluctuations is considered; this is necessary for safety analysis of storage containers during all periods of their operation on the storage platform.

In the DSNFSF of Zaporizhska NPP, ventilated containers (prototype of VSC-24 storage containers of Duce Engineering and Services Inc., USA) are used. The containers (Fig. 1) are placed on the open platform and are cooled by natural circulation of atmospheric air. Each container has 24 spent fuel assemblies from WWER-1000 reactors, placed into a tight storage cask. The cask is filled with the inert gas helium, which cools the spent fuel assemblies by natural circulation.

The detailed structure of a storage cask is presented in Fig. 2. The main components of the cask are spent fuel assemblies, metal guide tubes, and inert gas helium, which circulates between these elements. Inside the storage cask, spent fuel assemblies are numbered as shown in Fig. 2.

The decay heat of each fuel assembly was calculated by Zalyubovskii et al. [17]. Fig. 3 shows changes with time of storage. Because of the safety requirements, each fuel assembly should have not more than 1 kW of the decay heat generation before loading.

3. Methodology

Owing to the specifics of the investigated object, only numerical simulation was carried out. The effective methodology in this situation is to use conjugate heat transfer problems, which allow modeling of mutual heat transfer in solid and fluid media. The mathematical model includes [18]:

- Continuity equation
- Equation of motion of viscous gas
- Energy equation for fluids
- Heat conduction equation for solids
- Equations of k–ε turbulent flow model
- Ideal gas law for calculation of cooling air density
- Equations for calculating thermal properties of helium as dependent on temperature
- Equations that describe the radiative heat transfer

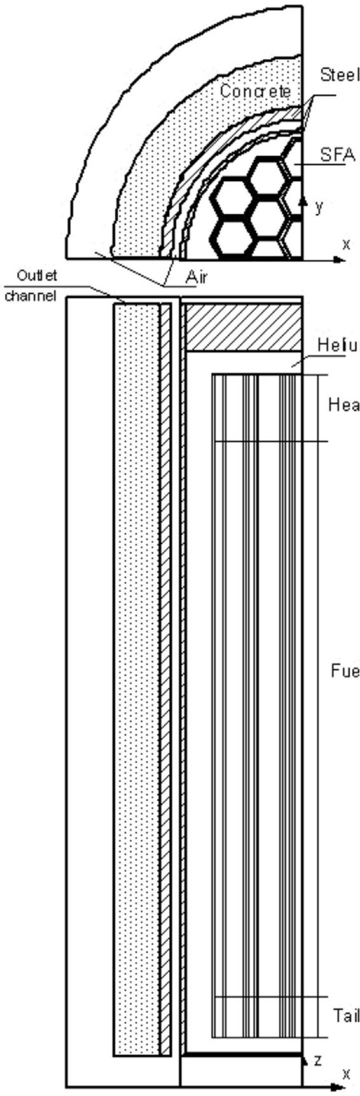

Fig. 4. Computational domain for ventilating container. SFA, spent fuel assembly.

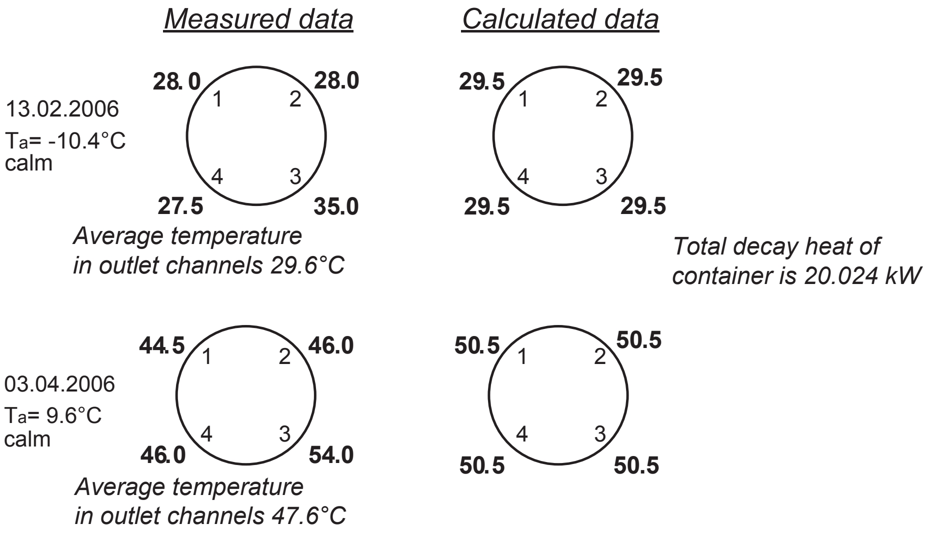

Fig. 5. Measured and calculated temperatures in outlet channels of container.

Equations are solved using standard program complexes, which are a methodology based on finite element methods.

For detection of the influence of outer temperature changes on the thermal state of containers with SNF, a computational model like the one presented in [19] was chosen (Fig. 4).

Computational domain includes one container with a small part of ambient air that consists of about 1.5 million nodes. Because of the container's symmetry, only a quarter of it was considered. The ventilation outlets were simplified and presented as straight channels; inlet vents were not considered. These simplifications have a small influence on the level of maximal temperature but do not influence the thermal "behavior" of the SNF. The inner structure of the storage cask was presented in a maximally detailed way: helium circulates between guide tubes and spent fuel assemblies. Spent fuel assemblies were presented as solid bodies with equivalent thermal properties according to the Safety Analysis Report [20].

For verification of the mathematical model and the solving methodology, the steady state problem was solved. The normal atmosphere pressure and temperature of ambient air were chosen as the boundary conditions. The results of verification are presented below.

The main problem was considered in transient formulation. The numerical results, which were obtained by Alyokhina et al. [18] (temperature profiles for solid and fluid bodies, velocity and pressure profiles of air and helium, all at 24°C ambient temperature), were used as the initial conditions. The temperature and the atmospheric pressure of ambient air were used as the boundary conditions.

For detection of the influence of the daily temperature fluctuation on the thermal state of the containers with SNF, several problems were considered. In each of them, atmospheric temperature T_a changes in a sinusoid manner around the average daily summer temperature:

$$T_a(\tau) = T_{aver} + C_0 \cdot \sin\left(2\pi \frac{\tau}{24}\right),$$

where T_{aver} is the average atmospheric temperature (24°C for territory of Zaporizhska NPP; °C); C_0 is the amplitude of daily temperature fluctuation (°C; here, we considered ±10°C, ±7°C, ±5°C); τ is the time of storage (hours).

During the calculations, only the summer temperature of ambient air varies.

All transient problems were considered for the beginning of SNF storage, so the decay heat of each fuel assembly was 909 W, which corresponds to the decay heat after unloading from the storage pool.

4. Results and discussion

Numerical investigations of the thermal processes in dry SNF storage were carried out in two stages. In the first stage, the steady state of the container was obtained and results were verified. The next stage was unsteady calculations.

First, the mathematical model and approach, based on conjugate heat transfer problems, were verified by comparing the calculated and measured temperatures of the ventilating air at the exit of the container. Temperature monitoring in DSNFSF is carried out by measurement of the temperature of the ventilating air in each of the outlet vents. Other measurements were not carried out during the containers operation, so verification could be done only by comparison of temperatures at the outlet vents.

Calculation was carried out for a container that had been operated on the storage platform since 2001. Two days with calm conditions of container operation were chosen for verification. Measured total decay heat and measured ambient temperature were taken as input data for simulation in the verification case. Results are presented in Fig. 5. In the figure, the measured data are presented on the left side and the calculated data are given on the right side. Channels are numbered inside the circle; outside the circle, the temperatures in degrees Celsius are presented. The difference between the calculated and the measured temperatures does not exceed 6°C for any of the channels or 3°C for the average temperature; however, this could be caused by local influence of outer factors (e.g., wind) at the measurement points. Several verification calculations were carried out, and results of each showed that the difference between the calculated and the measured temperatures does not exceed 5–6°C. Verification shows that the mathematical model and the calculation approach adequately describe the thermal processes in the storage container, so they can be used for the next investigations.

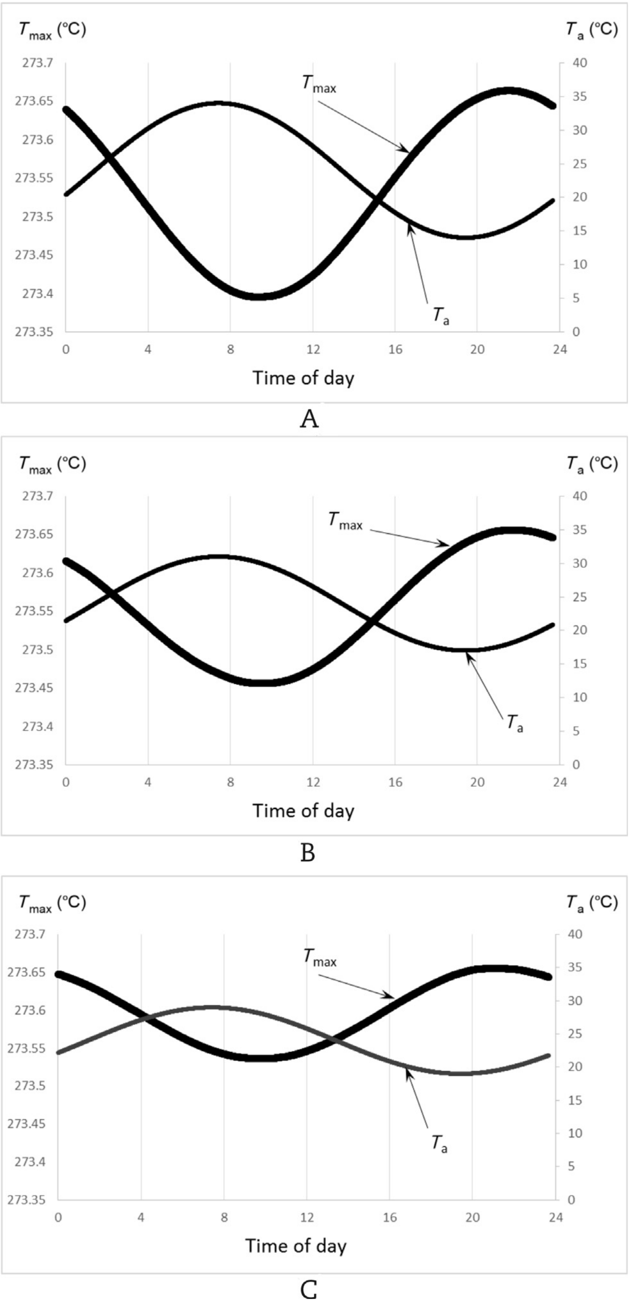

Fig. 6. Daily fluctuation of temperature. (A) ±10°C. (B) ±7°C. (C) ±5°C.

Table 1
Temperature data of fuel assemblies.

Fuel assembly no.	$T_{\text{aver asm}}$			C_{asm}			τ_{shift}
	$C_0 = \pm 5°C$	$C_0 = \pm 7°C$	$C_0 = \pm 10°C$	$C_0 = \pm 5°C$	$C_0 = \pm 7°C$	$C_0 = \pm 10°C$	
1	205.53	205.53	205.48	0.36	0.53	0.71	6.30
2	253.39	253.36	253.33	0.12	0.20	0.26	10.13
3	273.60	273.55	273.54	0.06	0.10	0.13	13.17
8	227.71	227.68	227.64	0.21	0.33	0.43	6.00
10	260.19	260.13	260.11	0.10	0.18	0.23	10.48
12	268.16	268.10	268.08	0.07	0.13	0.18	12.52
18	210.39	210.33	210.30	0.27	0.44	0.61	5.92
20	228.79	228.72	228.69	0.13	0.26	0.37	8.43

Detailed results of steady calculations for a single container, which are used as initial conditions, were presented by Alyokhina et al. [18]. The maximal temperature inside the storage cask ($T_{\max}$) is 273.5°C. The hottest assembly is assembly no. 3, placed in the center of the cask. The coolest assembly is assembly no. 1 because it is placed near the cask shell.

The changes of maximal temperature in the storage cask according to different outer influences are shown in Fig. 6. The calculation area, decay heat of assemblies, and initial conditions for each transient problem were the same.

The daily fluctuation of maximal temperatures inside the storage cask is not more than $\pm 0.134°C$ for $C_0 = \pm 10°C$ and decreases to $\pm 0.058°C$ for $C_0 = \pm 5°C$. The peaks of the fuel maximal temperature fluctuations are shifted relative to the peaks of daily temperature fluctuation at about 13.3 hours.

The temperature state of each fuel assembly inside the storage cask was also explored. The numerical experiment showed that the time variation of average temperature in each assembly T_{asm} looks like the daily fluctuation of maximal temperatures inside the storage cask and can be described by

$$T_{\text{asm}}(\tau) = T_{\text{aver asm}} + C_{\text{asm}} \cdot \sin\left(2\pi \frac{\tau - \tau_{\text{shift}}}{24}\right),$$

where $T_{\text{aver asm}}$ is the time averaging of T_{asm}, C_{asm} is the amplitude of the daily temperature fluctuation of T_{asm}, and τ_{shift} is the time delay of daily fluctuation of T_{asm}. The main parameters of the fuel temperature behavior are presented in Table 1.

Numerical investigation showed that the time shift relative to the peaks of daily temperature does not depend on the value of daily temperature fluctuation. The lowest time shift was detected for the assembly placed near the cask shell assembly no. 18 (see Fig. 2); the highest time shift was for assembly no. 3, which is placed near the center of the cask.

As we can see from Table 1, the coolest assembly is assembly no. 1, which is placed near the cask shell. However, the time shift for this assembly is greater than that for assembly nos. 8 and 18, which are placed further from the cask shell. This phenomenon probably happens because of a different mechanism of heat transfer. In the channel between assembly no. 1 and the cask shell, heat conduction through helium is dominant. Between the cask shell and assembly nos. 8 and 18, the distance is greater and the convection is more intensive, so heat transferred faster. Owing to this phenomenon, the time shift for assembly no. 18 is the smallest because this assembly has three out of six sides that are cooled intensively by convection.

5. Conclusions

The unsteady thermal processes inside a storage cask with SNF were investigated, and the dependence of the SNF thermal state on the daily temperature fluctuation was explored.

The maximal temperature is the main parameter in the monitoring of the SNF thermal state and one of the main factors in the development of preventive actions for possible accidents. The results of simulation showed that maximal temperature weakly depends on outer daily temperature fluctuations and has a delay of more than 13 hours. Therefore, it is acceptable to neglect the daily temperature fluctuation in the safety analysis. The assemblies that are placed near the cask shell are more susceptible to the influence of outer temperature fluctuation. So, this fact should be taken into account in the development of measures to prevent and eliminate the consequences of accidents (abnormal outer temperatures of ambient air, fire accidents, etc.).

Conflicts of interest

The authors declares that there is no conflict of interest regarding the publication of this paper.

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