THERMAL CONDUCTIVITY ENHANCEMENT OF NUCLEAR FUELS

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Abstract: The UO_2 thermal conductivity enhancement is a very complex problem. One of the possibilities to enhance the thermal conductivity it is to add another additive with specific properties to the matrix UO_2. There are represented the possibilities of thermal conductivity enhancement of uranium dioxide. There are different additives which can be used and one of the possible additives was selected for mathematical calculations to determine the temperature drop in the uranium dioxide pellet. The mathematical calculations were introduced in step-by-step form.

Keywords: uranium dioxide, thermal conductivity, beryllium oxide

1. INTRODUCTION

Nuclear reactors use nuclear fuels mostly in the form of uranium dioxide – UO_2 in the present. Uranium dioxide is a ceramic material with high hardness, chemical and thermal stability and low thermal conductivity due to the ionic bounds between atoms. The low thermal conductivity has very negative influence on the UO_2 performance during the burn-out cycle in the nuclear reactor.

As the consequence of low thermal conductivity and high volumetric heat generation in the nuclear fuel there is a high thermal gradient in the nuclear fuel pellet. As the consequence the pellet deforms, cracks and the fission gases release from it. All these processes can lead to the perforation of nuclear fuel cladding and contamination of the primary circuit of NPP by fission products. Moreover, significant amount of heat accumulates in the nuclear fuel pellet and it is necessary to lead the heat from the core in the case of loss of coolant accident (e. g. Fukushima accident).

For this reason it is very advantageous to increase the thermal conductivity of UO_2 for enhancement of safety of nuclear reactor operation.

2. OPTIONS OF UO_2 THERMAL CONDUCTIVITY ENHANCEMENT

Thermal conductivity of UO_2 depends on many parameters of the material and nuclear reactor operation – porosity, grain size, burn up etc. It is possible to influence the thermal conductivity by these parameters in limited scope but the influence is mainly negative – with increasing the parameters the thermal conductivity decrease.

It seems to be perspective to add another additive to the matrix of UO_2 recently. This additive should have significantly high thermal conductivity and low neutron absorption. In this case the total thermal conductivity of nuclear fuel pellet can be increased while the neutron balance will be influenced little (by significant amount of additive in the matrix of UO_2, the enrichment of nuclear fuel should be increased to keep the neutron balance of nuclear reactor).

Following additives are investigated in the present:

BeO – it is very well compatible with UO_2 matrix and its chemical stability is also excellent. It has very high thermal conductivity and small neutron absorption cross section [1]. On the other hand this material is very toxic and probably for this reason it will never be used in commercial scope.

SiC – does not have so high thermal conductivity like BeO, but it has no negative effect on human health and so no sanitary restriction are related to this material. The material has relatively high absorption cross section and for this reason nuclear fuel should be enriched to high level [2]. It might not easy to implement from legislative point of view.

Diamonds and carbon nanotubes – these materials have extremely high thermal conductivity and very low absorption cross section. Hygienic risks are acceptable. These materials have the highest probability that they will be used for thermal conductivity enhancement [3].

3. TEMPERATURE PROFILE CALCULATION OF NUCLEAR FUEL PELLET

3.1. TEMPERATURE PROFILE CALCULATION OF PURE UO_2 PELLET

In general the temperature profile of nuclear fuel pellet has parabolic shape, but the detail behavior is determined by many factors. For the case described in the paper only the influence of local temperature on the thermal conductivity will be concerned. Next it is assumed that the pellet has cylindrical shape and the material has isotropic properties uninfluenced by the structure. For these conditions the temperature profile of the UO_2 pellet can be described by the integral thermal conductivity [4]:

$$\int_{Tp}^{T} \lambda(T')dT' = \frac{q_H}{4\pi}\left(1 - \frac{r^2}{r_u^2}\right) \tag{1}$$

where $\lambda(T')$ is temperature dependence of thermal conductivity on temperature T', q_H is linear performance of the fuel rod, T_P is surface temperature of nuclear fuel pellet, T is radial temperature at he radial location r (r has the limits from 0 to pellet radius r_u).

Calculation of the temperature profile described by the eq. (1) is shown in the figure 1. For given surface temperature T_p the value of integral thermal conductivity is determined (by calculation or by the graph in the figure 1 and the increment on the y-axis is calculated from eq. (1) for particular radius r. The temperature at this radius can be read in reverse process: calculated value of the integral thermal conductivity on the y-axis determines particular value of the function which determines the temperature on the x-axis. In the case that the radius is equal to zero the temperature in the center will be calculated $T = T_C$. The temperature profile calculated by this method is shown in the figure 2.

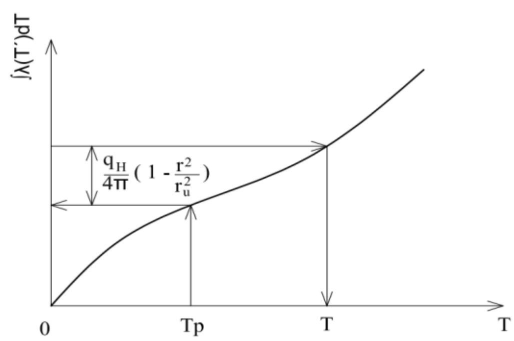

Fig.1: Function of the integral thermal conductivity as a dependence on temperature [4,eq. 2.33]

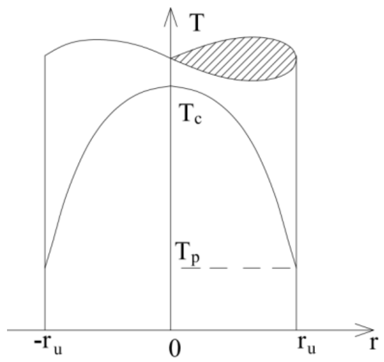

Fig. 2: Temperature profile in the UO_2 pellet [4]

3.2. TEMPERATURE PROFILE CALCULATION OF UO_2 PELLET WITH ADDITIVE

The additive is used to be added before the final sintering of pellet and it can have many shape forms (balls, needles, fibres) and size variations. In general it is possible to say that the best results can be reached in the case when the matrix of UO_2 and additive were in one phase (they would create molecular solution). But there are no techniques in the industrial application which would allow it, anyway it is possible to calculate the temperature profile in the mixed fuel pellet.

Temperature profile of the mixed nuclear fuel pellet is the same like in the previous case. Under the condition that the surface temperature is also the same, the eq. (1) can be modified to the form of eq. (2). The assumption is following: the thermal conductivity of mixture fuel is in direct proportion with the volumetric ratios of UO_2 matrix and additive.

$$(1-V_p)\int_{Tp}^{T}\lambda_{UO2}(T')dT' + V_p\int_{Tp}^{T}\lambda_p(T')dT' = \frac{q_H}{4\pi}\left(1-\frac{r^2}{r_u^2}\right) \tag{2}$$

There is V_p term in the eq. (2). This term is volumetric portion of additive in the volume of nuclear fuel pellet. If the additive has significantly higher thermal conductivity than UO_2 matrix, then the temperature profile is expected to drop in the mixture nuclear fuel pellet. Symbol $\lambda_p(T')$ stands for dependence of thermal conductivity of additive on the temperature.

4. RESULTS OF MATHEMATICAL MODELS

Followings parameters were chosen for theoretical calculations:

Linear thermal power of the fuel rod	q_H	30000	[W/mK]
Pellet radius	r_u	5	[mm]
Volumetric share of additive in the pellet	V_p	0.05	[-]
Surface temperature of the pellet	T_p	650	[°C]

Tab. 1: Input parameters for temperature profile calculation

The values were taken from an example in [4]. The mathematical function of the thermal conductivity and integral thermal conductivity of UO_2 were taken also from this reference. As the additive the BeO was chosen and its properties were found in [5]. There are only measured values of thermal conductivity for different temperatures in [5]. These values were fitted by a polynomial function of the fifth order and both of the functions are plotted in the figures 3 and 4. The UO_2 shows very low thermal conductivity and thermal conductivity of BeO is much higher than the thermal conductivity of UO_2.

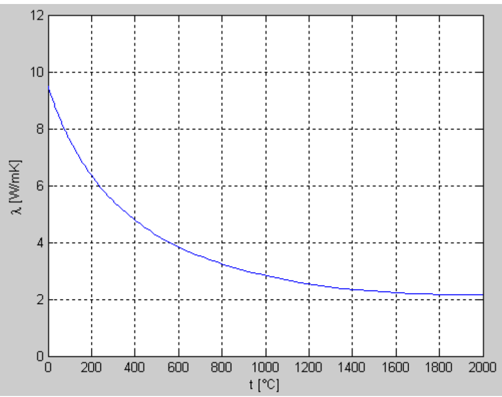

Fig. 3: Thermal conductivity of UO_2 as a function of temperature

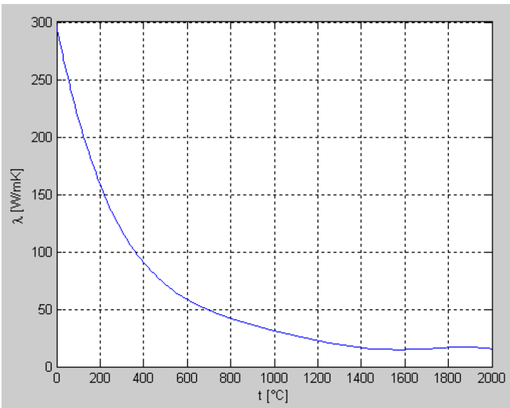

Fig. 4: Thermal conductivity of BeO as a function of temperature

Functions of thermal conductivity (figure 3 and figure 4) were integrated for the use in eq. (1) and (2) and result functions are plotted in the figure 5. There are three lines – the blue lines are the plotted integral thermal conductivity functions of UO_2 (the lower one) and BeO (the upper one) and the red line is the plotted integral thermal conductivity function of mixture nuclear fuel respectively.

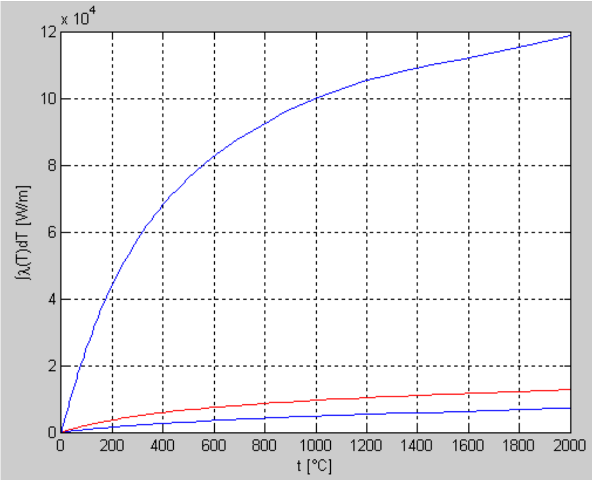

Fig. 5: Functions of integral thermal conductivities of UO_2, BeO and their mixture

The temperature profile of pure UO_2 fuel pellet was calculated from the eq. (1) and the temperature profile of mixed fuel pellet UO_2 + BeO was calculated from eq. (2). These two profiles are plotted in the figure 6 for further comparison.

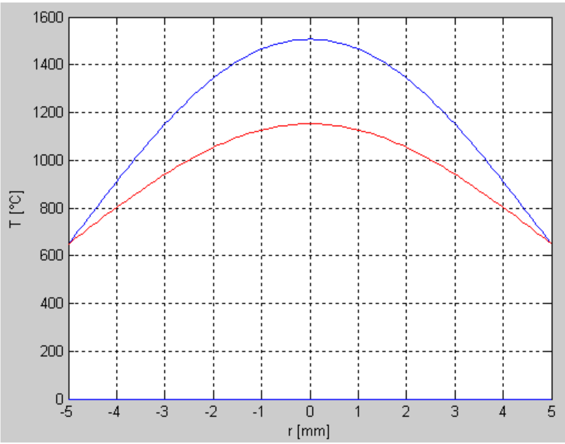

Fig. 6: Temperature profile in the pellet made of pure (blue line) and mixed (red line) nuclear fuel

As can be seen in the figure 6 – by adding 5 volumetric percent of BeO to the UO_2 pellet the temperature profile in the center of the pellet can be significantly decreased. As consequence the mechanical-thermal stress is reduced and the content of heat in the mixture fuel pellet is also lower.

5. SUMMARY

Simplified mathematical models were used to prove the fact that by addition of relatively small amount of BeO to the matrix of UO_2 the temperature profile in the nuclear fuel pellet can be significantly reduced. The temperature drop in the center is approx. 320 °C. However it is necessary to mention that the mathematical models were developed for maximally ideal conditions which are not possible to reach in the reality. But it is possible to use the simplified mathematical models for comparison of the influence of different additives on the temperature profile in the nuclear fuel pellet.

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