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NEUTRONIC ANALYSIS ON A LOW ENRICHED URANIUM COUPLED REACTOR CONSISTING OF PULSE CORES AND A LASER MODULE

Hiroki Takezawa and Toru Obara
Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology
2-12-1-N1-19, Ookayama, Meguro-ku, Tokyo, 152-8550, Japan.
takezawa@nr.titech.ac.jp; tobara@nr.titech.ac.jp

ABSTRACT

A highly enriched uranium coupled reactor consisting of pulse cores and a laser module is known as one of the reactors for nuclear-pumped laser. Neutronic analysis on a low enriched uranium coupled reactor which consists of pulse cores and a laser module was performed. Calculation results showed that a low enriched uranium coupled reactor could achieve criticality by using several expanded pulse cores and thermal expansion effect of the pulse cores was the most dominant in factors on feedback effect of the coupled reactor.

Key Words: Nuclear-pumped laser, Coupled reactor, Pulse reactor, Monte Carlo method.

1. INTRODUCTION

Utilization of nuclear-pumped laser could develop quite new applications of nuclear energy which has been used historically as heat source in nuclear reactors. Nuclear-pumped laser is produced typically by pumping laser active medium with charged particle beam such as electron or heavy ion, electric discharge, or nuclear reactions such as nuclear fissions. If the fission reactions in nuclear reactors are used to pump laser active medium, nuclear energy is directly converted to laser in nuclear reactors, and we can use nuclear energy not only as heat energy and electric energy but also as laser.

Theoretical and experimental study on nuclear-pumped laser has been performed in IPPE, and they have constructed a reactor for experiment of nuclear-pumped laser [1]. Their reactor is a coupled reactor which consists of pulse cores and a subcritical thermal laser module and uses highly enriched metallic uranium as fissile material, and has achieved nuclear-pumped lasing. Although their design is not a optimised design for practical use, the IPPE-type coupled reactor is one of reactors for nuclear-pumped laser.

On these backgrounds, we aims to design and to analyze a low enriched uranium coupled reactor for nuclear-pumped laser which consists of pulse cores and a subcritical thermal laser module as the first gateway to pass for providing our original practical design. In this aim, we selected the IPPE-type coupled reactor as the reactor we research because their reactor has achieved nuclear-pumped lasing and it is meaningful to investigate their philosophy of design for our original practical design. To achieve the aim, we need to perform the following three studies: to study whether the coupled reactor with low enriched uranium can achieve criticality or not, to develop a space-dependent kinetic analysis method, and to research applications of nuclear-pumped laser from the coupled reactor. The second study is necessary because the IPPE-type coupled reactor has unnegligible neutronic difference between fast pulse cores and a subcritical thermal laser module. Based on these information, we set two purposes for this study. First one is to study whether the coupled reactor with 20% enriched metallic uranium can achieve criticality or not. The IPPE's design uses highly enriched metallic uranium as fissile material in both the fast pulse cores and the subcritical thermal laser module. We used 20% enriched metallic uranium in both the pulse cores and the subcritical thermal laser module and performed criticality analysis. Second one is analysis of factors on feedback effect in the coupled reactor. This analysis was performed as a preparation for future kinetic analysis in order to make important factors on feedback effect clear in the coupled reactor.

2. NEUTRONIC ANALYSIS ON A LOW ENRICHED URANIUM COUPLED REACTOR

2.1. Criticality Analysis of a Low Enriched Uranium Coupled Reactor

In this analysis, we studied if the coupled reactor with 20% enriched metallic uranium achieve criticality or not. Also, we compared neutronic characteristics between the coupled reactor with 100% enriched metallic uranium and the coupled reactor with 20% enriched metallic uranium. criticality analysis was performed using a continuous energy Monte Carlo code MVP2.0 [2] and a nuclear data library JENDL3.3 under the condition that the number of histories per batch was 50000 and the number of batch was $5 + 80\ (\mathrm{skip} + \mathrm{tally})$.

2.1.1. Geometry of a coupled reactor

Fig. 1 shows a schematic view of a coupled reactor which imitates the coupled reactor designed in IPPE. This coupled reactor consists of two fast pulse cores and a subcritical thermal laser module. Each pulse core is a highly enriched metallic uranium cylinder with a radius of $11\,\mathrm{cm}$ and a height of $22\,\mathrm{cm}$, and includes no complex inner structures such as control rods and a reactivity regulator. A laser module consists of laser cell region, reflector region, and structure region, and has a radius of $1700\,\mathrm{mm}$ and a axial length of a $2500\,\mathrm{mm}$. The laser cell region is filled with laser cells, and the gap between laser cells is filled with polyethylene moderator.

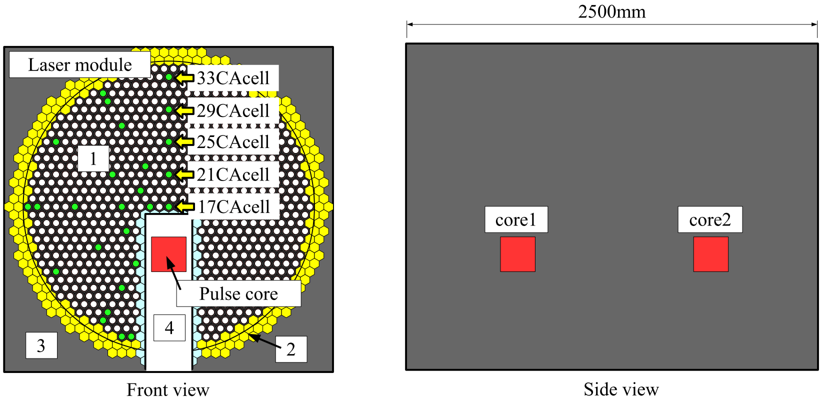

Figure 1. Schematic View of a Coupled Reactor (1: laser cell region, 2: reflector region, 3: structure region, 4: void region.)

Fig. 2 shows a schematic view of a laser cell designed by IPPE. A laser cell is a stainless steel tube with a outer diameter of $50\,\mathrm{mm}$, a inner diameter of $49\,\mathrm{mm}$, and a axial length of $2500\,\mathrm{mm}$. On the inner wall of a laser cell, highly enriched metallic uranium is coated with $5\,\mu\mathrm{m}$ thickness, and Ar and Xe are filled in a laser cell with partial pressure ratio 200 to 1.

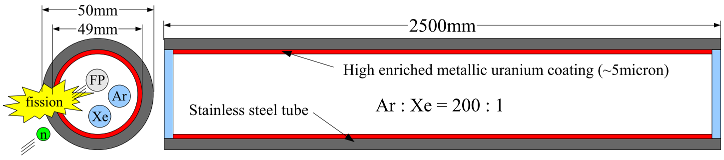

Figure 2. Schematic View of a Laser Cell

2.1.2. Calculation results of criticality analysis

First, uranium enrichment of both the pulse cores and the subcritical thermal laser module (Fig. 1) was set to $20\,\%$, and we tried to achieve criticality of the coupled reactor just by making the pulse cores and the laser module closer each other to increase neutron coupling between the componets. But, in this case, no criticality was achieved. Then, as a second step to achieve criticality, only the number of pulse cores was increased from 2 to 11. But, in this case, no criticality was also achieved. Then, as a third step, the size of the pulse cores was expanded with constant uranium density and the number of the pulse cores was increased to achieve criticality and uniform axial power distribution in the laser cells; second condition is needed to achieve uniform gas pumping in them.

One case where criticality was achieved is shown in Fig. 3 and Table I. In this case, there are 8 pulse cores in axial direction, and each pulse core has a radius of $13\,\mathrm{cm}$ and a height of $30\,\mathrm{cm}$.

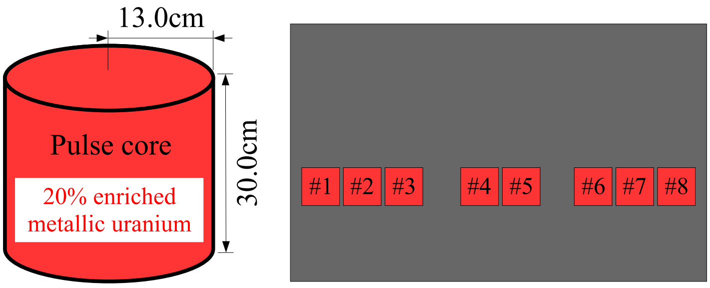

Figure 3. An Expanded Pulse Core and Side View of a Low Enriched Uranium Coupled Reactor with 8 Cores

Axial power distribution in 17CAcell, 21CAcell, $\cdots$, and 33CAcell (see Fig. 1) was evaluated in the geometry above (Fig. 3) and is shown in Fig. 4. X-axis and Y-axis shows axial position in laser cells and relative power per $5\,\mathrm{cm}$ laser cell respectively. This power distribution has two features: more uniform

Table I. k_{eff} of bare componets and the coupled reactor

	k_{eff}	σ [%]
Bare 8 pulse cores	0.8264	0.04
Bare laser module	0.1588	0.06
Coupled reactor	1.0067	0.04

axial power distribution in inner cells (17CA and 21CA) than that of a highly enriched uranium coupled reactor (see Fig. 5) and little power contribution of outer cells (25CA, 29CA, and 33CA).

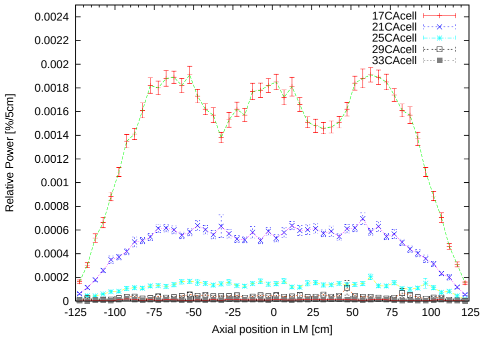

Figure 4. Axial Power Distribution in Laser Cells in a Low Enriched Uranium Coupled Reactor

Axial power distribution in IPPE-like design was also evaluated as a reference data and is shown in Fig. 5. This power distribution has also two features: existance of power peaks at pulse core positions ($\pm 50\,\mathrm{cm}$) and little power contribution of outer cells (25CA, 29CA, and 33CA).

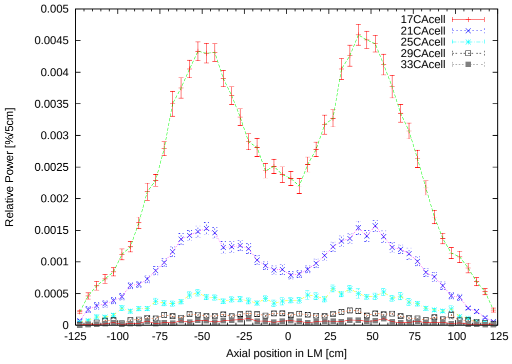

Figure 5. Axial Power Distribution in Laser Cells in High Enriched Uranium Coupled Reactor

2.1.3. Summary of criticality analysis

Calculation results showed that a 20% enriched uranium coupled reactor could achieve criticality just by increasing the uranium mass of pulse cores. Furthermore, uniform axial power distribution in the inner laser cells in the 20% enriched uranium coupled reactor was achieved by positioning 8 pulse cores in axial direction . This means that the number of pulse cores needed to flatten axial power distribution in laser cells is about 8 if the design of the laser module is not changed. Calculation results also showed that both radial and axial uniform gas pumping is impossible in IPPE-like coupled reactor design because of its nonuniform power distribution in both radial and axial directions. In designing a practical coupled reactor for nuclear-pumped laser, we need not only to achieve nuclear-pumped lasing but also to achieve uniform gas pumping for more effective direct energy conversion.

2.2. Analysis of Factors on Feedback Effect

It is necessary to make important factors on feedback effect clear for future kinetic analysis of pulsed neutron flux in the coupled reactor. There are two main candidate factors on feedback effect: thermal expansion effect and neutronic temperature effect. Neutronic temperature effect includes thermal neutron spectrum shift in the laser module and increase of resonance absorption by doppler effect in the pulse cores and the laser module. In this section, we studied what factors are the most important for feedback effect.

2.2.1. Temperature distribution in the laser module

From the results in previous section, one can easily assume that there is a temperature distribution in a laser cell or in a laser module. We first evaluated the temperature distribution dividing the laser module into six regions: two radial regions and three axial regions (see Fig. 6). For instance, a region which is included in radial region 1 and axial region 2 is named as R1A2.

Calculation results are shown in Table II. If the temperature of the pulse cores with the maximum relative power increases 100 K, temperature increase in each region of the laser module was much smaller than or almost equal to 1 K. This means that thermal expansion of the laser module can not be included in the factors on feedback effect. Moreover, it is assumed that neutronic temperature effect of the laser module on feedback effect is also small because of its small temperature increase.

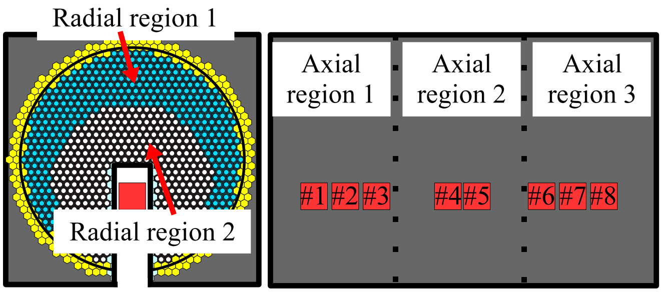

Figure 6. Divided Six Regions in the Laser Module

Table II. Distribution of Temperature Increase in Each Region of the Reactor

Region	Relative Power $[\%]$	ΔT [K]	Ratio
Pulse core(#1 or #8)	15.53	55.41	1.001
Pulse core(#2 or #7)	28.03	100.0	1.001
Pulse core(#3 or #6)	26.04	92.89	1.001
Pulse core(#4 or #5)	23.53	83.95	1.001
R1A1 and R1A3	0.35	0.09	1.000
R1A2	0.24	0.12	1.000
R2A1 and R2A3	3.90	0.93	1.000
R2A2	2.37	1.14	1.000

2.2.2. Study on feedback effect in the 20% enriched uranium coupled reactor

With the temperature distribution in each region of the coupled reactor, we studied feedback effect in the 20% enriched uranium coupled reactor. Calculation results are shown in Fig. 7. X-axis and Y-axis is temperature of the pulse core with the maximum relative power and effective multiplication factor of the coupled reactor respectively. The blue plot shows effective multiplication factor with the following three points considered: neutronic temperature effect in the laser module, thermal expansion effect in the pulse cores, and neutronic temperature effect in the pulse cores. In contrast, the green plot shows effective multiplication factor with the only one point considered: thermal expansion effect of the pulse cores. If the temperature of the pulse cores with the maximum relative power rises $100\,\mathrm{K}$, these two plots are very close to each other; therefore, we concluded that the thermal expansion effect of the pulse cores was the most dominant for feedback effect of the 20% enriched uranium coupled reactor.

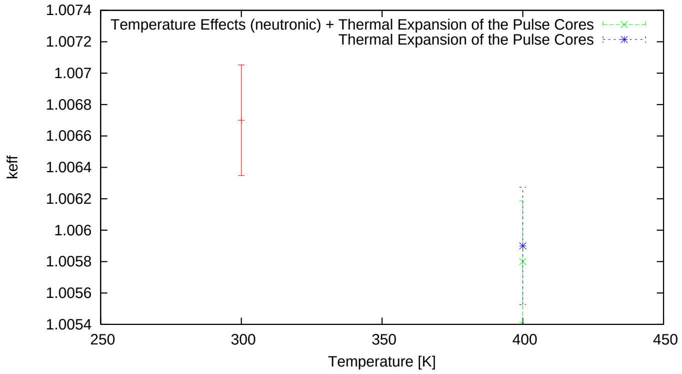

Figure 7. Feedback Effect in the Low Enriched Uranium Coupled Reactor

3. CONCLUSIONS

We performed neutronic analysis on the 20% enriched uranium coupled reactor which consists of pulse cores and the subcritical thermal laser module. Firstly, we studied the possibility that a low enriched uranium coupled reactor could achieve criticality or not. In this criticality analysis, calculation results showed that the 20% enriched uranium coupled reactor could achieve criticality with increasing the uranium mass of the pulse cores and the number of the pulse cores and without changing the design of the laser module. Calculation results of power distribution showed that both radial and axial uniform gas pumping was impossible in a coupled reactor with IPPE-like design, but only axial uniform gas pumping could be possible by positioning several pulse cores properly in axial direction. The number of the pulse cores needed to flatten axial power distribution in laser cells was about 8. Secondarily, we evaluated temperature distribution in the laser module and then studied factors on feedback effect in the coupled reactor for future kinetic analysis. In this study, we showed that thermal expansion effect of the laser module was negligible and neutronic temperature effect of the laser module was small because of its small temperature rise of smaller than or almost equal to $1\,\mathrm{K}$ when the temperature of the pulse cores with the maximum relative power rose $100\,\mathrm{K}$. Furthermore, we showed that thermal expansion effect of the pulse cores was the most dominant as a factor on feedback effect in the low enriched uranium coupled reactor.

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