Differences between Light Water and Heavy Water as Reflector in a Channel of CANDU6

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1. Introduction

Although atomic weight difference between light water (LW) and heavy water (HW) is only 2 and fundamental chemical difference doesn't exist because of number of position in each atom composing the molecule, there are a lot of differences. Somebody said that even a mosquito can notice the discrepancy of LW and HW. Although we have several categories such as neutronics, economics, chemistry, physics and so on, we can find that there are so many differences between LW and HW, indeed.

In nuclear industry, this difference in neutronics affect type of Nuclear Power Plant (NPP) so that everything related with a type of NPP differ from each other. For instances, refueling period, burnup of the fuel, loading scheme and so on. A point is that this difference results in enormous consequence. We have 4 CANDU6 type reactors including stopped NPP-Wolsong 1-, permanently while the others are type of Light Water Reactor (LWR).

Even though Wolsong unit 2~4 have type of CANDU6, LW exists as well as heavy many place in the nuclear reactor. Actually, there is more LW compared with HW. Except for the primary heat transport system (PHTS) and moderator system in the calandria tank-about one hundred tons for PHTS and two hundred and fifty tons for moderator system, all the others are filled with LW.

Specifically, there is a compartment, end shield at the each end of channels along with refueling direction-refueling direction is regarded as axial direction in the CANDU system. This region is filled with LW and steel balls instead of HW to seal and block the radiation from the core so that we can minimize the penetration of the radiation which may cause hazard to workers and material. At this point a question that what will happen to the core and other things if we use HW instead of LW and steel balls arises.

The volume of end shield region is relatively small compared with those of PHTS and moderator system. Thus the cost for replacing the LW with HW will not that much. In addition, the HW can maximize the neutron economy because it doesn't kill neutron too much and gets neutrons back to the core again. Augmentatively, it can contribute to the flattening of power and neutron flux for axial direction instead of just lowering power and neutron flux in the end regions.

In this paper, the specific numerical experiment will be done regarding reflector material in a channel problem. A comparison between usage of LW and HW will be conducted by using finite element analysis [1, 2].

2. Comparison of LW and HW

As mentioned in the previous section, Introduction, we have many differences in many aspects. Although, in this paper, most effective aspect is neutronics, other things are also introduced as well. Most important virtue of moderator is slowing down ration rather that slowing down power.

Table I. Important Figure of Merits(FOMs) as Moderator for Several Materials

Materials	Slowing Down Power ($\xi\Sigma_s$)	Slowing Down Ratio ($\xi\Sigma_s / \Sigma_a$
H	-	-
D	-	-
H_2O	1.35	71
D_2O	0.176	5670
He	$1.6X10^{-5}$	83
Be	0.158	143
C	0.060	192
^{238}U	0.003	0.0092

Although both slowing down power and slowing down ratio are important for the moderation, slowing down ratio is rather treated frequently compared with slowing down power because it includes neutron economics as well. The HW has overwhelming value compared with other candidates for slowing down ratio as shown in Table I. The slowing down ratio of graphite is about 165, referentially. In Table I, the hydrogen and deuterium is gas phase at room temperature. Additional information on neutronics and physics are listed as well in Table II.

Table II. Physical Information for Several Materials

Materials	Atomic Weight (A)	Density (ρ ,g/cm^3)	# Collision from 2Mev to 1eV
H	1	Gas	14
D	2	Gas	20
H_2O	(18)	1.0	16
D_2O	(20)	1.1	29
He	4	Gas	43
Be	9	1.85	69
C	12	1.60	91
^{238}U	238	19.1	1730

As shown table II, a tendency that atom with low atomic weight requires less collision counts compared with heavy nuclides. Although density of HW just 10% larger than LW, number of collision necessary to specific energy level is about twice compared with LW. Despite of this facts, the slowing down ratio is extremely better that LW, surprisingly.

Although it is extra story compared with main stream, the price of HW is profoundly expensive compared with that of LW. About three hundred dollars for a kilogram of HW.

It is generally known that the thermal-hydraulic properties such as specific heat, thermal conductivity, heat capacity and so son are similar to each other. But due to the heat from the core, if hydrogen and deuterium gas build up, the differences becomes clear [3].

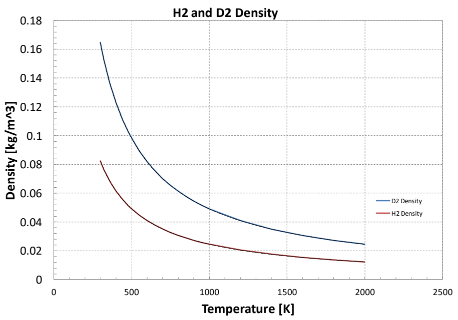

Fig. I. Densities of H_2 and D_2

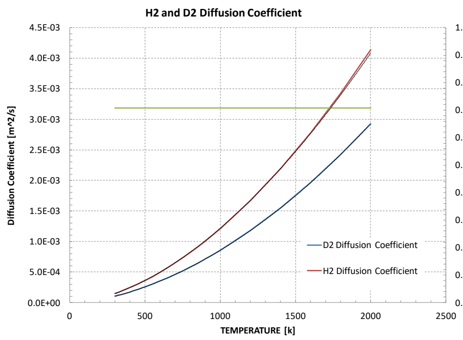

Fig. II. Diffusion Coefficients of H_2 and D_2

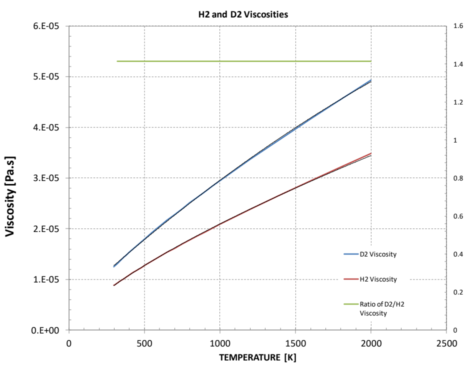

Fig. III. Viscosities of H_2 and D_2

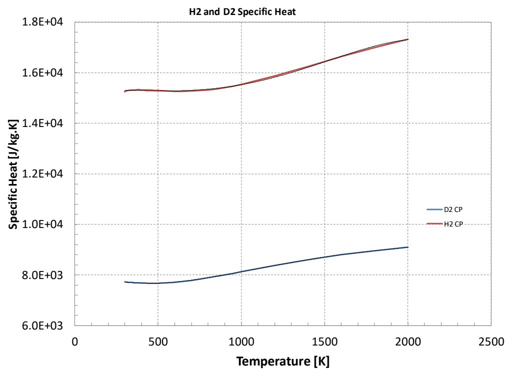

Fig. IV. Specific Heats of H_2 and D_2

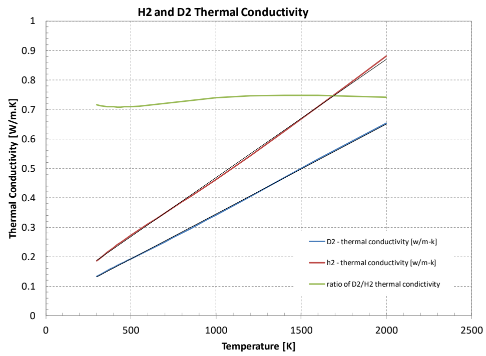

Fig. V. Thermal Conductivities of H_2 and D_2

As shown in Fig. I-V, once phase transform from liquid to gas by providing heat from the core, the difference become effective. Because deuterium has twice atomic weight compared with hydrogen, densities are double for all temperature interval. Other properties also show that there are huge differences for viscosity, diffusion coefficient, specific heat, density and thermal conductivity.

3. Finite Element Analysis for Different Reflector

In the original SuPer Homogenization (SPH) factor (SPH Fac.) study, the axial reflector region is not considered because conventional neutronics calculation which was done by using the RFSP code and etc didn't dealt with those regions rigorously. But in this study, we took into account those regions and took a look to see what happens.

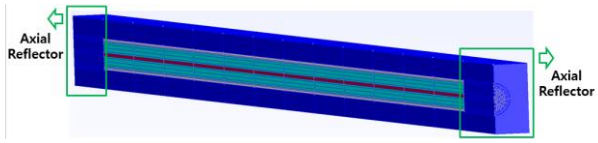

Fig. VI. Channel Modeling

As shown in Fig. VI, two materials are examined for axial reflector. One is HW, our suggestion, another is LW, close to real core material-although steel balls are not taken into account, it is assumed that similar behavior can be observed. HW cross section for the neutronics analysis is produced by lattice calculation of the McCARD code [4]. LW cross section is just taken from the famous C5G7 benchmark problem. Thus, actual reaction rate for each type of reaction is different from each other, rigorously. But in this paper, it is assumed that overall, rough characteristics between those of McCARD continuous cross sections and those of LW in C5G7 benchmark cross section are similar to each other.

This analysis is done with two group cross sections and the multiplication factor, power and thermal & fast fluxes will be compared for two cases of reflectors. Although core module of finite element method (FEM) code is based on the diffusion equation which is not adequate to the lattice-like calculation, the SPH factor is applied to make up the low order weakness of the analysis.

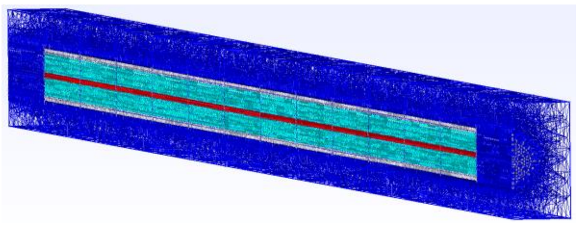

Fig. VII. Channel Meshing

Table III. Eigen Value with HW and LW

	Boundary Condition	HW	LW
Without SPH Fac.	Reflective	1.12978 (922)	1.12171 (1027)
	Vacuum	1.12432 (1078)	1.12171 (1029)
With SPH Fac.	Reflective	1.11761 (-295)	1.11215 (71)
	Vacuum	1.11196 (-158)	1.11215 (73)

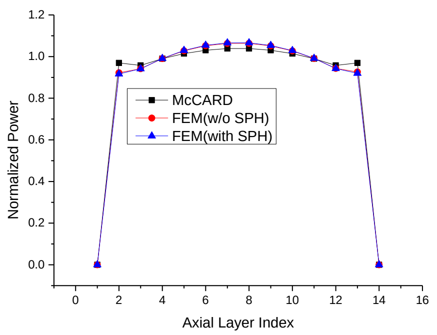

Fig. VIII. Power Distributions for HW and Reflective B.C. Situation

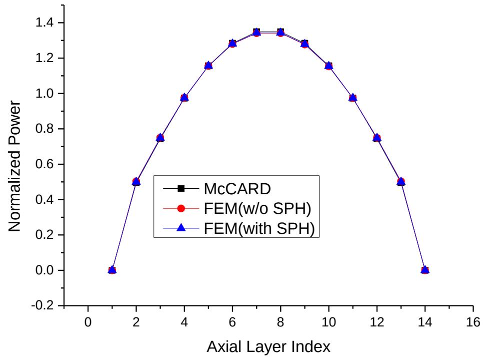

Fig. IX. Power Distributions for HW and Vacuum B.C. Situation

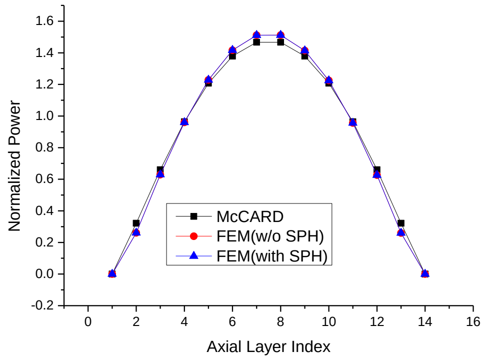

Fig. X. Power Distributions for LW and Reflective B.C. Situation

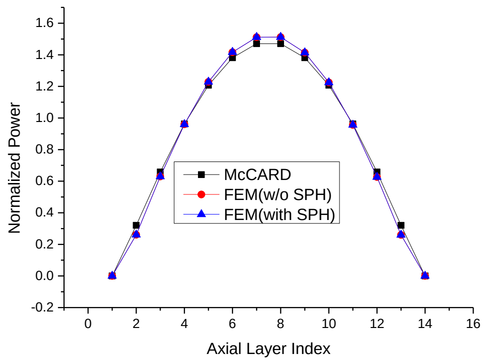

Fig. XI. Power Distributions for LW and Vacuum B.C. Situation

It is shown in Fig. VIII~XI that using SPH factor doesn't affect axial distribution at all because that the SPH factor only related with radial distribution. Despite of type of boundary conditions and problems (HW or LW), the FEM results well match with the McCARD code which was used as the reference. In Fig. XI, we can verify that the light water acts as a kind of absorber so that the power distribution around boundary between fuel and axial reflector (between layer 1&2 and 13&14) shrinks.

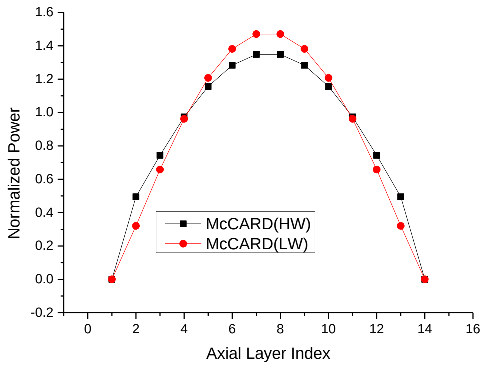

Fig. XII. Comparison of Power Distributions for HW and LW through McCARD

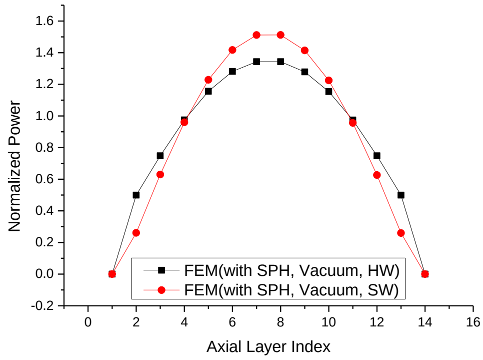

Fig. XIII. Comparison of Power Distributions for HW and LW through a FEM code

By taking a look into Fig. XII and Fig. XIII, using HW will give us more flat power distribution compared with LW, relatively. Because HW take neutrons back to the core instead of eliminating them, while LW terminates neutrons inside of it. This comes from the large slowing down ratio of HW compared with LW. Naturally, HW has better neutron economy.

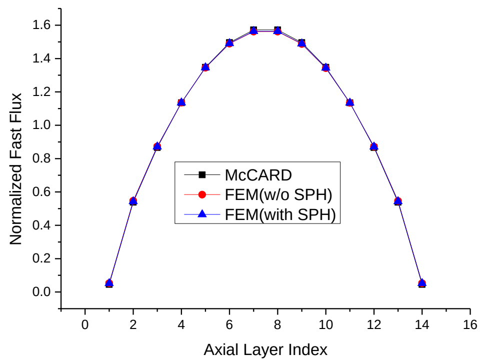

Fig. XIV. Fast Flux Distributions for HW and Reflective B.C. Situation

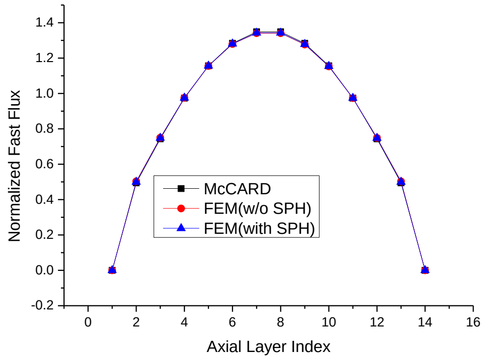

Fig. XV. Fast Flux Distributions for HW and Vacuum B.C. Situation

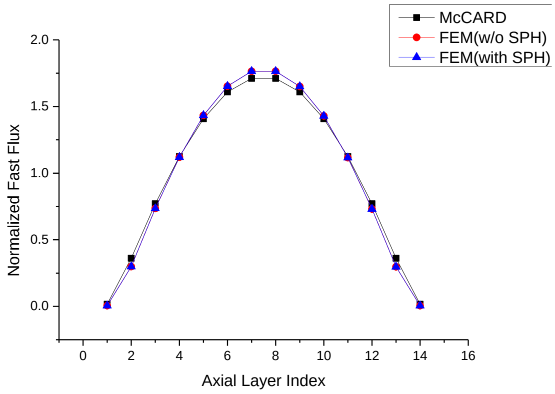

Fig. XVI. Fast Flux Distributions for LW and Reflective B.C. Situation

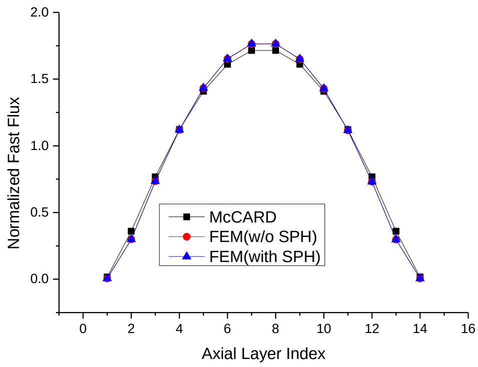

Fig. XVII. Fast Flux Distributions for LW and Vacuum B.C. Situation

Because of using C5G7 cross section, the multi-group results using the FEM code is slightly different from the McCARD code. But this discrepancy can be acceptable as inductive conclusion by considering many experimental cases. Same trend appears for all results regarding power, fast flux and thermal flux.

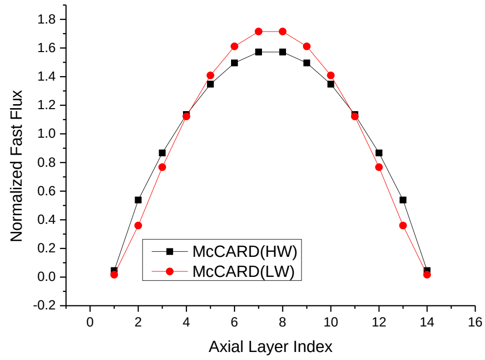

Fig. XVIII. Comparison of Fast Flux Distributions for HW and LW through McCARD

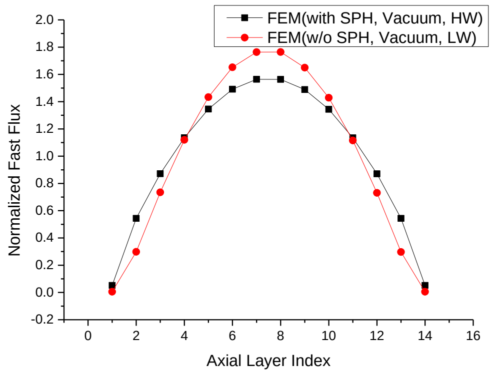

Fig. XIX. Comparison of Fast Flux Distributions for HW and LW through a FEM code

Because that that the fast flux is result of nuclear fission, the fast flux distribution naturally is similar to the power distribution. Also, due to the moderation effect in the reflector region, the fast flux ratio is the reflector region diminish rapidly as it goes to the both ends. Same as power distribution, using HW make us have more flattened fast flux distribution by analyzing Fig. XVIII and XIX.

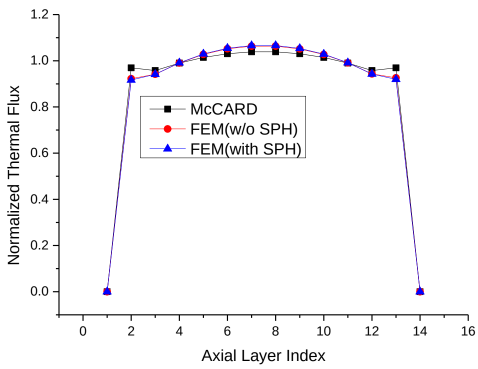

Fig. XX. Thermal Flux Distributions for HW and Reflective B.C. Situation

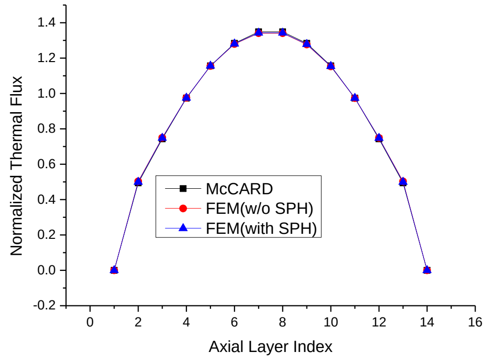

Fig. XXI. Thermal Flux Distributions for HW and Vacuum B.C. Situation

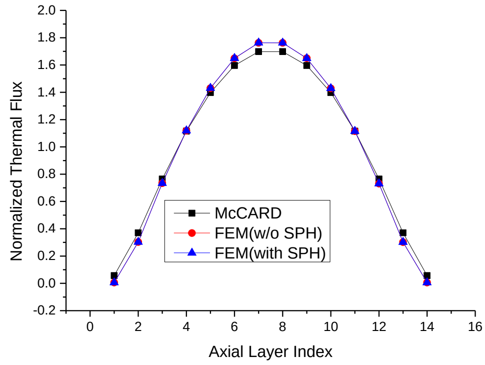

Fig. XXII. Thermal Flux Distributions for LW and Reflective B.C. Situation

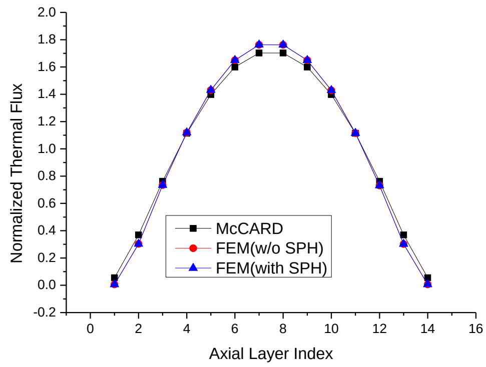

Fig. XXIII. Thermal Flux Distributions for LW and Vacuum B.C. Situation

The thermal flux distribution for reflective boundary condition with HW really resembles power distribution for reflective boundary condition with HW. Due to the almost negligible absorption in the reflector regions, the thermal flux and power distribution for reflective B.C. condition with HW is almost flat for entire region. Same tiny discrepancy between Monte Carlo code and multi-group code for appears in Fig. XXII and XXIIII.

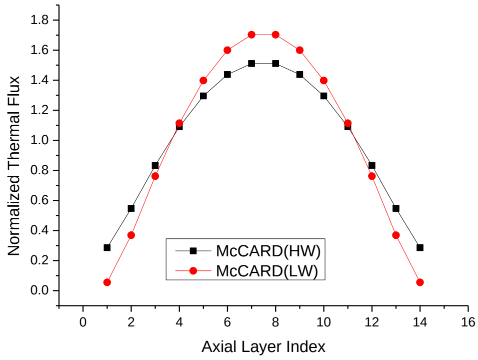

Fig. XXIV. Comparison of Fast Flux Distributions for HW and LW through McCARD

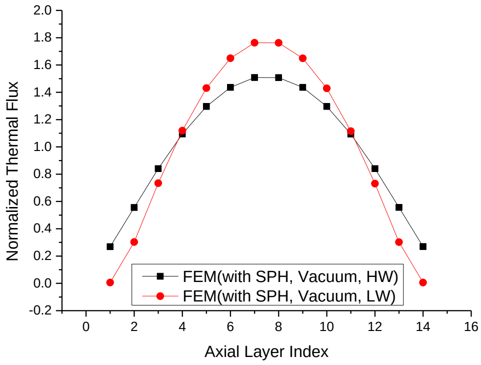

Fig. XXV. Comparison of Fast Flux Distributions for HW and LW through a FEM Code

Same flattening effect occurs for the thermal flux distribution. Although scattering power of LW is greater than the HW, the thermal flux in the HW reflector region is larger than that in the LW reflector. It means that HW make neutron alive in the reflector region so that more neutron can go back to the core.

4. Conclusions

In this study, HW as alternative reflector is tested numerically instead of LW with McCARD and a FEM code. As we verified in the previous section, the HW doesn't kill neutron and retain their population so the they sometimes go back to the fuel and make more fission. In addition, although fast & thermal flux is higher in both ends along with axial direction when the HW is used as reflector, it seems that still the magnitude is not that big.

It this study, the HW effect as reflector is investigated quantitatively. Although the price of HW is extremely higher than the LW, it can be a measure to improve neutron economy in the core. Also, vital properties such as slowing down ratio and slowing down power are verified as well. It is recommended that the HW is used as axial reflector in any type of reactor instead of LW and steal ball in the future.

Acknowledgement

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REFERENCES

[1] E. H. Ryu and H. G. Joo, Finite Element Method Solution of the Simplified P_3 Equations for General Geometry Applications, Vol.56, p. 194-207, 2013.
[2] E. H. Ryu and et al., Reproduced of Transport Solution in the PHWR Channel Calculation with the SPH Factors and the Albedo Control, PHYTRA5, 2020.
[3] Sunil Nijhawan, Hydrogen – Deutrium and other combustible gases, 2016.
[4] H. J. Shim and C. H. Kim, "McCARD User's Manual Version 1.0".