Gazi Üniversitesi
Fen Bilimleri Dergisi
PART C: TASARIM VE TEKNOLOJİ

Gazi University
Journal of Science
PART C: DESIGN AND TECHNOLOGY

GU J Sci, Part C, 12(2): 596-604 (2024)

Utilization Of Magnesium Chloride (Mg-Cl) Cycle for Hydrogen Production of Sombrero Fusion Reactor

Gamze ŞENER[1,*] Adem ACIR[1,2]

[1]*Gazi University, Graduate School of Natural and Applied Sciences, Department of Nuclear Science, Ankara, 06000, Türkiye*

[1,2]*Gazi University, Faculty of Technology, Department of Energy Systems Engineering, Ankara, 06000, Türkiye*

Article Info

Research article
Received: 21/05/2024
Revision: 26/05/2024
Accepted: 28/05/2024

Keywords

SOMBRERO fusion reactor
Mg-Cl
Hydrogen
Neutronic
Tritium

Makale Bilgisi

Araştırma makalesi
Başvuru: 21/05/2024
Düzeltme: 26/05/2024
Kabul: 28/05/2024

Anahtar Kelimeler

SOMBRERO füzyon reaktörü
Mg-Cl
Hidrojen
Nötronik
Trityum

Graphical/Tabular Abstract (Grafik Özet)

In this study, neutronic analysis of the sombrero fusion reactor at different fuel ratios was performed and the amount of hydrogen production was analyzed through the Mg-Cl cycle. / Bu çalışmada sombrero füzyon reaktörünün farklı yakıt oranlarında nötronik analizi yapılmış ve hidrojen üretim miktarı Mg-Cl çevrimi yoluyla analiz edilmiştir.

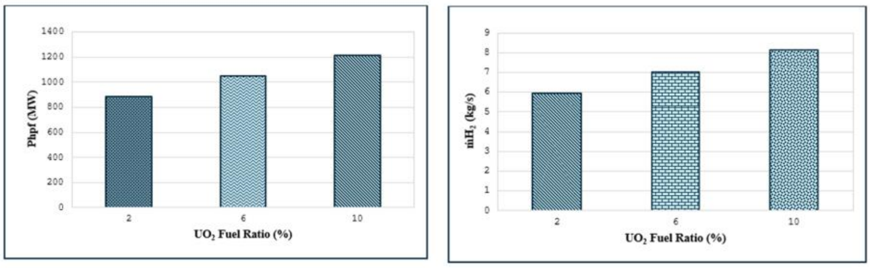

***Figure A**: The effect of UO_2 fuel rate on thermal power and hydrogen production /**Şekil A:** UO_2 yakıt oranının termal güce ve hidrojen üretimine etkisi*

Highlights (Önemli noktalar)

- *Neutronic analysis and hydrogen production analysis in the Sombrero fusion reactor. / Sombrero füzyon reaktöründe nötronik analiz ve hidrojen üretim analizi.*
- *Hydrogen production via magnesium chloride cycle. / Magnezyum klorür çevrimi aracılığıyla hidrojen üretimi.*
- *The effect of UO_2 nuclear fuel ratio on the amount of hydrogen production. / UO_2 nükleer yakıt oranının hidrojen üretim miktarına etkisi.*

Aim (Amaç): *Investigation of the effect of fuel ratio on hydrogen production in Sombrero fusion reactor. / Sombrero füzyon reaktöründe yakıt oranının hidrojen üretimine etkisinin araştırılması.*

Originality (Özgünlük): *Analyzing the hydrogen production potential at different fuel ratios in the Sombrero fusion reactor. / Sombrero füzyon reaktöründe farklı yakıt oranlarında hidrojen üretim potansiyelinin analiz edilmesi.*

Results (Bulgular): *The $\dot{m}_{H_2}$ have been computed as 5,92 kg/s for 2% UO_2 fuel ratio whereas; this value has been obtained as 8,13 for 2% UO_2 fuel ratio. / %2 UO2 yakıt oranı için $\dot{m}_{H_2}$ 5,92103 kg/s olarak hesaplanırken; %2 UO2 yakıt oranı için bu değer 8,12686 olarak elde edilmiştir.*

Conclusion (Sonuç): *As the UO2 fuel ratio increased, the amount of hydrogen production also increased. / UO_2 yakıt oranı arttıkça hidrojen üretim miktarı da artmıştır.*

*Corresponding author, e-mail: gamze.sener@gazi.edu.tr
DOI: 10.29109/gujsc.1487776

GU J Sci, Part C, 12(2): 596-604 (2024)

Gazi Üniversitesi
Fen Bilimleri Dergisi
PART C: TASARIM VE TEKNOLOJİ

Gazi University
Journal of Science
PART C: DESIGN AND TECHNOLOGY

http://dergipark.gov.tr/gujsc

Utilization Of Magnesium Chloride (Mg-Cl) Cycle for Hydrogen Production of Sombrero Fusion Reactor

Gamze Şener[1,*] Adem Acır[1,2]

[1]*Gazi University, Graduate School of Natural and Applied Sciences, Department of Nuclear Science, Ankara, 06000, Türkiye*

[1,2]*Gazi University, Faculty of Technology, Department of Energy Systems Engineering, Ankara, 06000, Türkiye*

Article Info

Research article
Received: 21/05/2024
Revision: 26/05/2024
Accepted: 28/05/2024

Keywords

SOMBRERO Fusion reactor
Mg-Cl
Hydrogen
Neutronic
Tritium

Abstract

The aim of this study is to investigate the hydrogen production potential of the magnesium chloride (Mg-Cl) cycle in the SOMBRERO fusion reactor. Three different percentages of UO_2 nuclear fuel, namely 2%, 6% and 10%, have been used while keeping the fuel zone thickness constant. The performance of the SOMBRERO fusion reactor has been considered statically. The neutronic calculations have performed with Monte Carlo neutron transport code. Firstly, it has been determined that the tritium breeding ratio (TBR) and energy multiplication factor (M) values depends on neutronically. Secondly, the amount of hydrogen production with by using energy multiplication factor (M) have been performed. The highest hydrogen production has been obtained as 8,12687 kg/s for 10% UO_2 fuel ratio.

SOMBRERO Füzyon Reaktörünün Hidrojen Üretiminde Magnezyum Klorür (Mg-Cl) Döngüsünün Kullanımı

Makale Bilgisi

Araştırma makalesi
Başvuru: 21/05/2024
Düzeltme: 26/05/2024
Kabul: 28/05/2024

Anahtar Kelimeler

SOMBRERO füzyon reaktörü
Mg-Cl
Hidrojen
Nötronik
Trityum

Öz

Bu çalışmanın amacı SOMBRERO füzyon reaktöründe magnezyum klorür (Mg-Cl) döngüsünün hidrojen üretim potansiyelini incelemektir. Yakıt bölgesi kalınlığı sabit tutularak %2, %6 ve %10 olmak üzere üç farklı UO_2 nükleer yakıt yüzdesi kullanılmıştır. SOMBRERO füzyon reaktörünün performansı statik olarak değerlendirilmiştir. Nötronik hesaplamalar Monte Carlo nötron transport kodu yarmıyla yapılmıştır. Öncelikle trityum üretim oranı (TBR) ve enerji çoğaltım faktörü (M) değerlerinin nötronik olarak hesaplanmıştır. İkinci olarak enerji çoğaltım faktörü (M) kullanılarak hidrojen üretimi miktarı araştırılmıştır. En yüksek hidrojen üretimi %10 UO_2 yakıt oranında 8,12687 kg/s olarak elde edilmiştir

1. INTRODUCTION (GİRİŞ)

With the increasing demand for energy today, the environmental impact of the methods used to generate the necessary energy is also on the rise. The interest in renewable energy has consequently surged. Hydrogen is a clean energy sources in meeting this energy demand [1]. The idea of nuclear hydrogen production, which aims to utilize the heat generated in nuclear reactors more efficiently, has emerged as a result. There are many studies in the literature on this subject. Ghorbani et. al.,[2] derived various thermochemical cycles such as Fe-Cl, Cu-Cl, Co-Cl, Mg-Cl, HyS, V-Cl, Ce-Cl S-I and Zn-S-I cycles as regards thermo-eco-environment. Oruç et al. [3] examined by using various Fe-Cl, Mg-Cl, S-I, HyS, and Cu-Cl, processes in the systems the thermo-eco-environment. Razi et al., [4] performed H_2 generation by using of Cu-Cl, Fe-Cl and Mg-Cl for waste heat for industrial steel plants. Özdemir et al. [5] used Mg-Cl, H2SO4 and UT-3 cycles in the solar assisted Brayton and Rankine in terms of energy and exergy. Asal and Acır [6] performed the produced hydrogen amount in the LIFE fusion reactor by using cobalt chloride (Co-Cl) process. Juárez-Martínez et al. [7] investigated production of

*Corresponding author, e-mail: gamze.sener@gazi.edu.tr
DOI: 10.29109/gujsc.1487776

hydrogen with by using S-I cycle for various heat exchangers under conditions. Özkaya et al. [8] performed hydrogen production in the PACER fusion concept with Fe-Cl cycle. Asal and Acır [9] examined hydrogen production in LIFE engine with Cu-Cl process under various conditions. Demir [10] applied hydrogen production in the SOMBRERO blanket with SMR method. Acır and Özkaya [11] investigated hydrogen production with Fe-Cl and Mg-Cl cycle in the PACER concept. Genç [12] presented hydrogen production with S–I, SMR and HTE cycles in the APEX. Balta et al. [13] computed exergy and energy efficiency under various conditions for hydrogen production with the Mg-Cl cycle. Asal et al., [14] performed exergy and energy efficiency under various conditions for hydrogen production with the Mg-Cl cycle in the HTR-PM.

In this study, the neutronic performance and hydrogen production with hydrogen unit in integrated SOMBRERO fusion blanket have been performed. The neutronic calculations have been computed with Monte Carlo calculation method for 2%, 6% and 10% UO_2 fuel ratios. Firstly, the tritium breeding ratio (TBR) and energy multiplication factor (M) have been calculated. Secondly, the hydrogen production with Mg-Cl cycle in the SOMBRERO fusion blanket have been examined and compared.

2. MATERIALS AND METHODS (MATERYAL VE METOD)

2.1. SOMBRERO Fusion Reactor (Sombrero Füzyon Reaktörü)

Sombrero fusion reactor designed by W. J. Schafer Associates researcher team. The SOMBRERO names descripted SOlid Moving BREeder ReactOr [15]. The original reactor design has been given in Fig. 1.

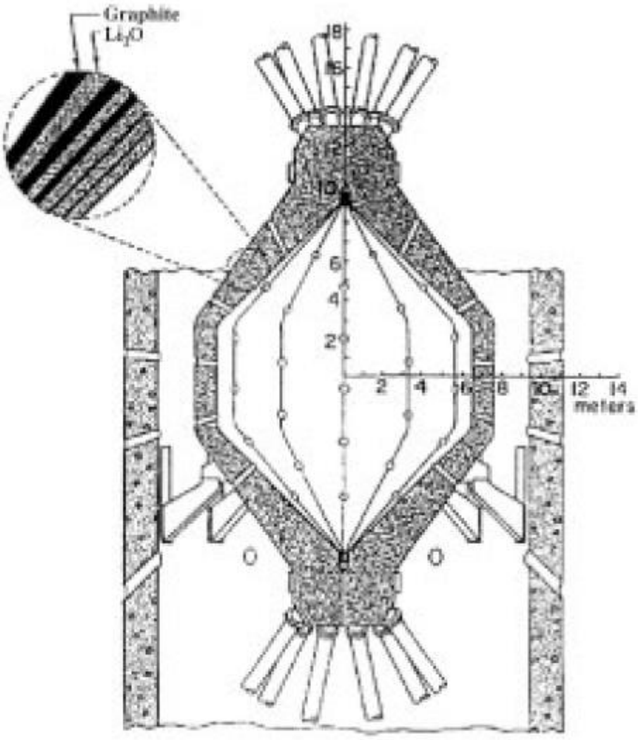

Fig. 1. SOMBRERO fusion blanket section view (SOMBRERO füzyon reaktörü kesit görünüşü)

The conceptual designed of a 1000 MWe KrF laser-driven IFE power plant. The SOMBRERO systematic view used in the calculations has been given in Fig. 2 The first wall (FW) material has been used C/C composite with 1 cm thick. The SOMBRERO blanket consists of three zones various Li enrichment. The first zone consists of 3% C/C composite and 97% Li_2O solid breeder with 19 cm thickness.

The second zone have 20% C/C composite and 80% Li_2O solid breeder with 40 cm thickness whereas, the third zone is 50% C/C composite and 50% Li_2O solid breeder with 40 cm thickness. The first zone

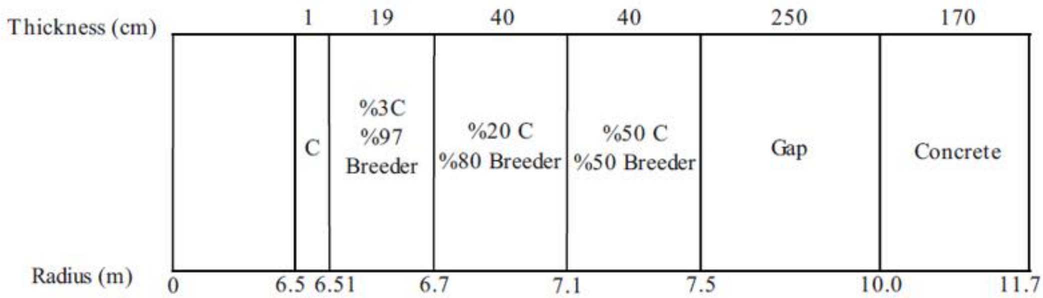

Fig. 2. SOMBRERO blanket structure (SOMBRERO blanket geometrisi)

has $UO_2 + Li_2O$ mixed of the different ratios. These ratios have been selected 10%, 6%, and 2% UO_2 in the LiO_2. The technical properties have been given in Table 1 [15].

2.2. *Magnesium Chloride Cycle* *(Magnezyum Klorür Döngüsü)*

In the calculations have been used the three step Mg-Cl thermochemical cycle. The reaction steps have been given as below:

$$MgCl_{2(s)} + H_2O_{(g)} \rightarrow MgO_{(s)} + 2HCl_{(g)} \quad (450°C) \quad (1)$$
$$MgO_{(s)} + Cl_{2(g)} \rightarrow MgCl_{2(s)} + 1/2O_{2(g)} \quad (450°C) \quad (2)$$
$$2HCl_{(g)} \rightarrow H_{2(g)} + Cl_{2(g)} \quad (80°C) \quad (3)$$

Table 1. Technical Properties of the Sombrero Fusion Reactor (Sombrero Füzyon Reaktörünün Teknik Özellikleri) [15]

Parameter	Value
Fusion Power, Pi	304 MW
Blanket thermal power, Pf	2677 MW
Fusion energy gain, Q	8,806
Alpha particles fraction	0.2
Neutron particles fraction	0.8
Efficiency of intermediate heat exchanger	0.8
Efficiency of driving system	0.5
Efficiency of gas turbine	0.6
Isotope separation system fraction	0.05
Auxiliary system fraction	0.05
Power ratio constant	2,363
Reaction efficiencies	0.9
Required electricity power	289.5 kJ/mol
Total required thermal power	122.5 kJ/mol

The first step is the hydrolysis reaction. The reaction actualized at 450–550°C. The second step at between 450°C and 500°C temperature occurred and called chlorination reaction. The third reaction is electrolysis reaction which can occur at 70–90°C temperature [16,17]. The Mg-Cl systematic view have been illustrate in Fig 3.

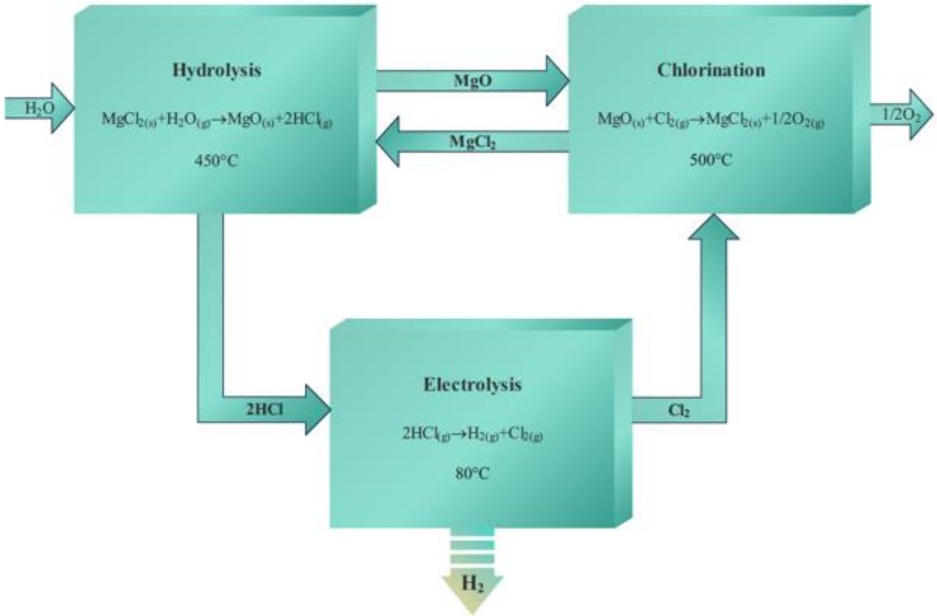

Fig. 3. Mg-Cl thermochemical cycle systematic view (Mg-Cl termokimyasal yöntemin sistematik görünümü)

The heat required (Q, kW) during a process is calculated by Eqs. (14-6) [9,18,19].

$$\dot{Q}_{in} + \dot{W}_{in} + \sum n_{in} H_{in} = \dot{Q}_{out} + \dot{W}_{out} + \sum n_{out} H_{out} \tag{4}$$

$$Q = \sum n_{out} \left(\bar{h}_f^o + \bar{h} - \bar{h}_0\right)_{out} - \sum n_{in} \left(\bar{h}_f^o + \bar{h} - \bar{h}_0\right)_{in} \tag{5}$$

$$\bar{h}(T) - \bar{h}_0 = AT + B\frac{T^2}{2} + C\frac{T^3}{3} + D\frac{T^4}{4} - \frac{E}{T} + F - H \tag{6}$$

where , $\dot{W}$ is work (kW), h is enthalpy (kJ/kg), $\bar{h}_f^o$ is enthalpy of formation (kJ/mol), $\bar{h}_0$ is standard enthalpy (kJ/mol), A, B, C, D, E, F, H values in the equation given in Eq. (6) are obtained from the Shomate Table 2 [19]. T is calculated as 1/1000 of the cycle temperature determined in K.

The static performance calculation of the SOMBRERO fusion reactor performed using the MCNP neutron transport code [20]. Three different percentages of UO_2 were used as fuel (2%, 6%, 10%). Li_2O has been chosen as the tritium breeder. With the obtained data, the TBR and M values were calculated. Using the relevant parameters of the reactor and the M values, the 1-ψ and P_{hpf} data were calculated.

Table 2. Required Mg- Cl cycle data for Shomate equation

Compounds	$\bar{h}_f^\circ$ (kJ/mol)	T (K)	A	B	C	D	E	F	H
$MgCl2_{(s)}$	-641,62	723-773	78,30733	2,435888	6,858873	-1,72897	-0,72991	-667,582	-641,616
$H2O_{(g)}$	-241,83	723	30,092	6,832514	6,793435	-2,53448	0,082139	-250,881	-241,826
$MgO_{(s)}$	-601,24	723-773	47,25995	5,681621	-0,87267	0,1043	-1,05396	-619,132	-601,241
$HCl_{(g)}$	-92,31	723-353	32,12392	-13,4581	19,86852	-6,85394	-0,04967	-101,621	-92,312
$Cl2_{(g)}$	0	773-353	33,0506	12,2294	-12,0651	4,38533	-0,15949	-10,8348	0
$O2_{(g)}$	0	773	30,03235	8,772972	-3,98813	0,788313	-0,7416	-11,3247	0
$H2_{(g)}$	0	353	33,06618	-11,3634	11,43282	-2,77287	-0,15856	-9,9808	0

3. RESULTS AND DISCUSSION (Sonuçlar ve Tartışma)

In order for fusion reactors to be self-sustainable, TBR must be greater than 1.05. Tritium production is produced from liquid and solid fuels containing lithium. In this reactor, the solid fuel containing lithium is Li_2O. As given in Eqs. (7-9), TBR has been calculated by the sum of T_6 and T_7, which include endothermic and exothermic reactions [8,9].

$$^{6}Li + n \rightarrow T_6 + He + 4.786 \text{ MeV} \quad (7)$$

$$^{7}Li + n \rightarrow T_7 + He + 2.467 \text{ MeV} \quad (8)$$

$$TBR = T_6 + T_7 \quad (9)$$

TBR values obtained in the SOMBRERO fusion reactor have been given in Fig. 4. TBR values have been obtained as approximately 1.31 in the fuel range containing 2% and 10% UO_2. It can be seen from the results obtained that the reactor provides self-sustainability.

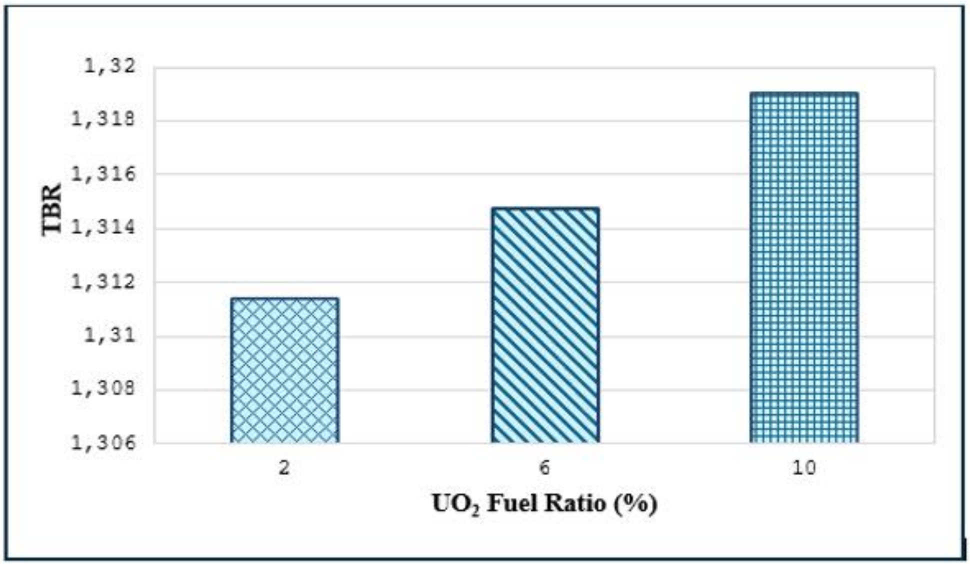

Fig. 4. Variation of tritium breeding (TBR) for various fuel ratio (Farklı yakıt oranı için trityum üretim değişimi)

Energy production occurs as a result of the reactions occurring in the Li_2O and UO_2 fuel mixture located in the first region of the Sombrero fusion blanket structure. The energy generated as a result of the reactions occurring in the fuel region is called the energy multiplication factor, as shown in Eq. (4) [8,9].

$$M = \frac{200 \text{ MeV} * <\phi * \Sigma_f> + 4.786 \text{ MeV} * T_6 - 2.467 \text{ Mev} * T_7}{17.6 \text{ MeV}} + 1 \quad (10)$$

Fig. 5 shows the change in M depending on the fuel ratio. The M value has been obtained as 1,31322 for 2% UO_2 + 98% Li_2O

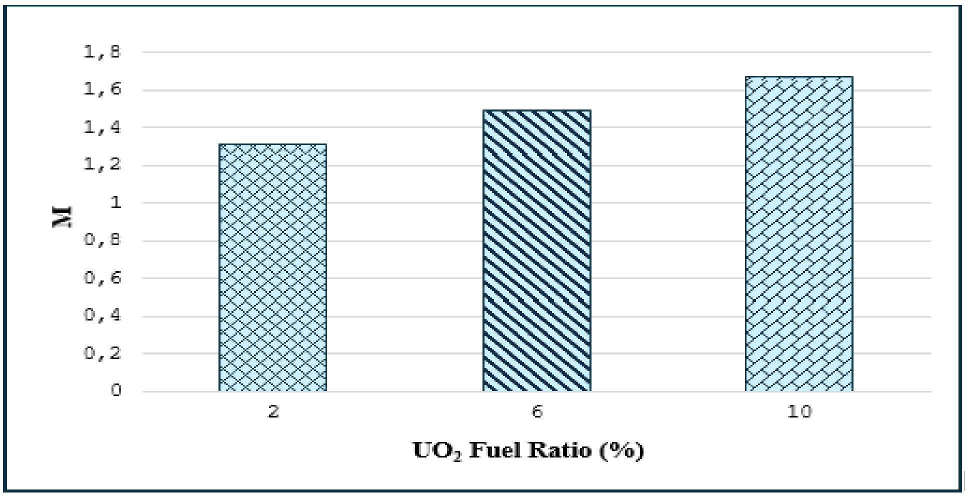

Fig. 5. Variation of energy multiplication factor (M) for various fuel ratio (Farklı yakıt oranı için enerji çoğaltım faktörü değişimi)

While the M value for 6% UO_2 + 94% Li_2O have been obtained as 1,49052, this value have been computed as 1,67014 for 10% UO_2 + 90% Li_2O. As seen in Fig. 5, it has been observed that the M value increased with the increase in fuel ratio. This increase is due to the fission reaction occurring in the fuel region depending on the fuel ratio. In other words, since the fission rate was higher for 10% UO_2 + 90% Li_2O, the M value has been highest in this parameter.

The thermal power ratio and total thermal power used in hydrogen production for the Mg-Cl thermochemical cycle are obtained from the following Eqs (5,6) [6,8,9].

$$1-\psi = 1-\frac{1}{\eta_{ihx}*\eta_{ds}[Q*(x_a+x_n*M)+1]*[\eta_{gt}+\varepsilon]}+\frac{\varepsilon}{[\eta_{gt}+\varepsilon]}+\frac{x_{aux}+x_{isf}}{\eta_{ihx}+[\eta_{gt}+\varepsilon]} \quad (11)$$

$$P_{hpf} = (1-\psi)*(1+\varepsilon)*\eta_{ihx}*\frac{P_f}{Q}*[Q*(x_a+x_n*M)+1] \quad (12)$$

The hydrogen mass flow equations for the Mg-Cl thermochemical cycle with the help of the Eqs. (7-15) given below [6,8,9]:

$$\dot{m}_{MgCl_2} = \frac{P_{hpf}}{q_{tot}} \quad (13)$$

$$\dot{m}_{H_2O} = \dot{m}_{MgCl_2} \times \frac{M_{H_2O}}{M_{MgCl_2}} \quad (14)$$

$$\dot{m}_{MgO} = \dot{m}_{MgCl_2} \times \frac{M_{MgO}}{M_{MgCl_2}} \times \eta \quad (15)$$

$$\dot{m}_{HCl} = 2 \times \dot{m}_{MgCl_2} \times \frac{M_{HCl}}{M_{MgCl_2}} \times \eta \quad (16)$$

$$\dot{m}_{Cl_2} = \dot{m}_{MgO} \times \frac{M_{Cl_2}}{M_{MgO}} \quad (17)$$

$$\dot{m}_{MgCl_2-2} = \dot{m}_{MgO} \times \frac{M_{MgCl_2}}{M_{MgO}} \times \eta \quad (18)$$

$$\dot{m}_{O_2} = 0,5 \times \dot{m}_{MgO} \times \frac{M_{O_2}}{M_{MgO}} \times \eta \quad (19)$$

$$\dot{m}_{H_2} = 0,5 \dot{\times} m_{HCl} \times \frac{M_{H_2}}{M_{HCl}} \times \eta \quad (20)$$

$$\dot{m}_{Cl_2} = 0,5 \times \dot{m}_{HCl} \times \frac{M_{Cl_2}}{M_{HCl}} \times \eta \quad (21)$$

The thermal power ratio $(1-\psi)$ and total thermal power (P_{hpf}, MW) required in the SOMBRERO fusion reactor integrated Mg-Cl hydrogen product unit have been given in Fig. 6 and 7. The $1-\psi$ and P_{hpf} with increasing UO_2 fuel ratio have been increased.

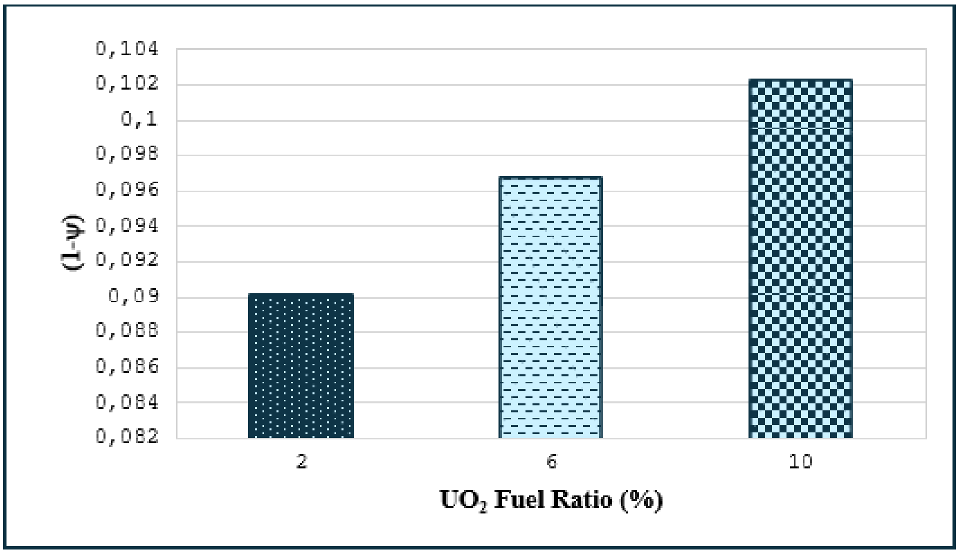

Fig. 6. Variation of thermal power ratio $(1-\psi)$ for various fuel ratio (Farklı yakıt oranı için termal güç oranı değişimi)

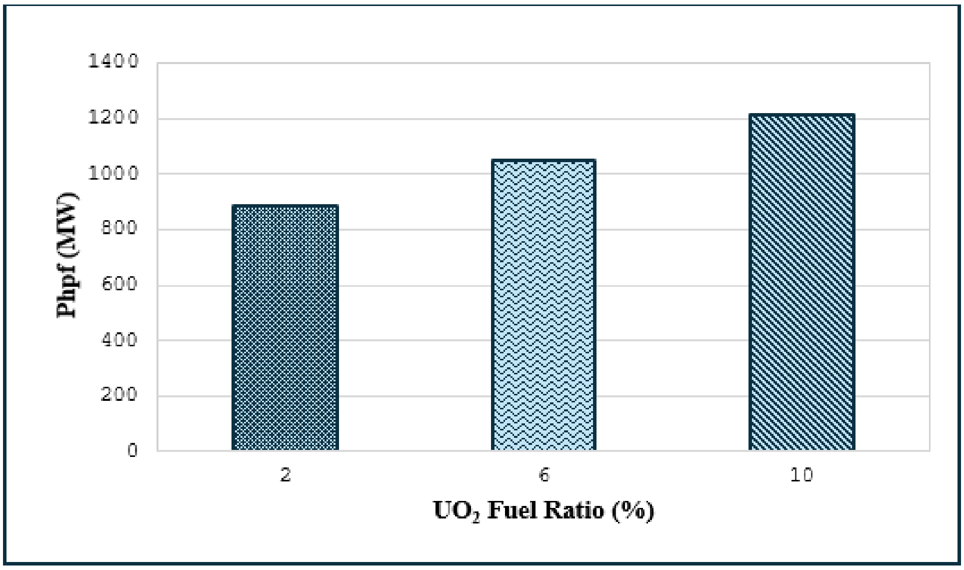

Fig. 7. Variation of total thermal power (P_{hpf}, MW) for various fuel ratio (Farklı yakıt oranı için toplam termal güç değişimi)

The $1-\psi$ have been obtained as between 0,09006 and 0,10222, the P_{hpf} have been computed as between 884,92461 MW and 1214,59578 for 2% UO_2 and 10% UO_2, respectively.

The hydrogen production ($\dot{m}_{H_2}$) for various fuel ratios have been illustrated in Fig. 8.

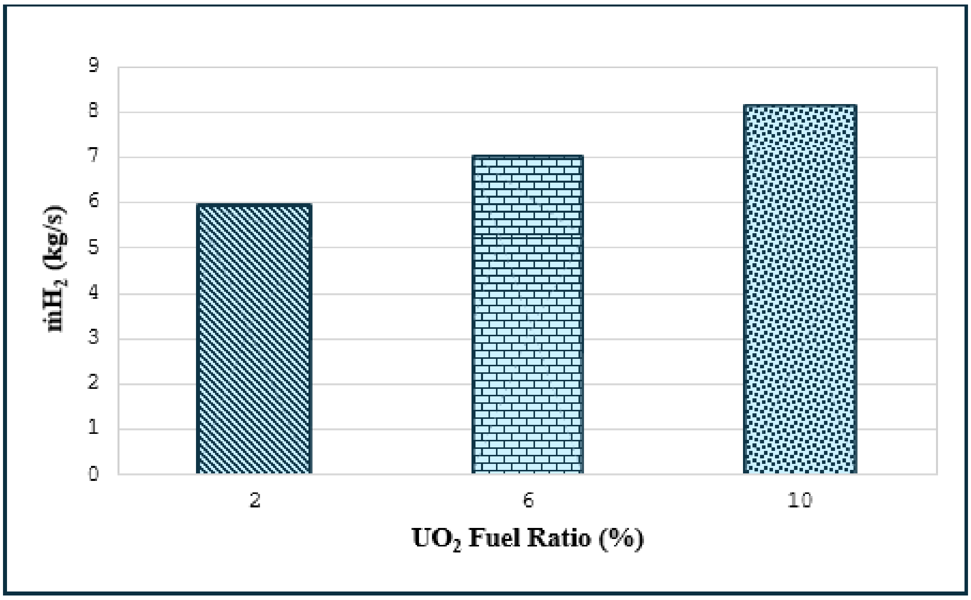

Fig. 8. Variation of hydrogen production ($\dot{m}_{H_2}$) for various fuel ratio (Farklı yakıt oranı için hidrojen üretimi değişimi)

The hydrogen production depending on the increase in M, which has generated due to fission reaction increasing fuel ratio, value have been increased.

The $\dot{m}_{H_2}$ have been computed as 5,92103 kg/s for 2% UO_2 fuel ratio whereas; this value has been obtained as 8,12686 for 2% UO_2 fuel ratio as shown in Fig. 8.

Table 3. Hydrogen production values various thermochemical process and reactor (Hidrojen üretim değerleri çeşitli termokimyasal proses ve reaktör)

Reference	**Type**	**Cycle**	**Produced Hydrogen Amount (kg/s) (Initial value)**
Present work	SOMBRERO fusion reactor	Mg-Cl	5.92-8.12
Ref. [21]	PACER fusion reactor	Fe-Cl cycle	~13
		Mg-Cl (Option I) Mg-Cl (Option II)	~39 ~26
Ref. [9]	LIFE fusion reactor	Cu-Cl cycle	1.39
Ref. [8]	PACER fusion reactor	Fe-Cl cycle	7.36/10.96
Ref. [10]	SOMBRERO fusion reactor	SMR+WGS	33.00
Ref. [12]	APEX fusion reactor	SMR+WGS+MCS	218
		SMR+WGS	100
		SMR	60
		THE	8.60
		S-I cycle	8.40
Ref. [14]	HTR-PM reactor	Mg-Cl	2.43

The hydrogen production results obtained in this study have been compared with the hydrogen production results obtained for different thermochemical processes and reactors given in the literature in Table 3. Generally, the hydrogen production has been good performance in the compared the hydrogen production in the SOMBRERO fusion reactor with literature results.

4. CONCLUSION (SONUÇLAR)

In this study, the hydrogen production potential of the Mg-Cl (magnesium chloride) cycle in the SOMBRERO fusion reactor have been investigated. The findings obtained as a result of the study are presented below:

- The tritium breeding ratio have been obtained as about 1.31 between %2 UO_2 + %98 Li_2O and %10 UO_2 + %90 Li_2O fuel.
- The energy multiplication factor (M) have been computed as the range of 1.31 and 1.67 between %2 UO_2 + %98 Li_2O and %10 UO_2 + %90 Li_2O fuel. The M have been increased with higher UO_2 fuel.
- The hydrogen production has been calculated as 5.92 kg/s for %2 UO_2 + %98 Li_2O whereas, these value have been computed as 8.12 kg/s for %10 UO_2 + %90 Li_2O.
- The hydrogen production with Mg-Cl has been good exhibited performance in the in the SOMBRERO fusion reactor compared with literature. In future work, the hydrogen production with new types of thermochemical processes will be examined in line with the results obtained by using different reflectors, tritium production materials and different fuels in the SOMBRERO fusion reactor

DECLARATION OF ETHICAL STANDARDS (ETİK STANDARTLARIN BEYANI)

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Yazarlar, bu makalede rapor edilen çalışmayı etkileyecek gibi görünen, birbiriyle rekabet halinde olan herhangi bir finansal çıkar veya kişisel ilişkinin bulunmadığını beyan etmektedir.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

***Gamze ŞENER*:** She carried out the numerical analysis, analyzed the results and wrote the article.

Sayısal analizleri yapmış, sonuçlarını analiz etmiştir ve makalenin yazım işlemini gerçekleştirmiştir

Adem ACIR: He performed the writing process and supervising.

Yazım sürecini ve süpervizörlüğü gerçekleştirdi.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

REFERENCES (KAYNAKLAR)

[1] Veziroğlu T. N. and Şahin S. 21st Century's energy: Hydrogen energy system. Energy Convers. Manag. 2008; 49(7):1820–31.

[2] Ghorbani B, Zendehboudi S, Zhang Y, Zarrin H, Chatzis I. Thermochemical water-splitting structures for hydrogen production: Thermodynamic, economic, and environmental impacts. Energy Conversion and Management 2023; 297:1117599.

[3] Oruc O, Dincer I. Assessing the potential of thermo-chemical water splitting cycles: a bridge towards clean and sustainable hydrogen generation. Fuel 2021; 286:119325.

[4] Razi F, Hewage K, Sadiq R. A comparative assessment of thermodynamic and exergoeconomic performances of three thermochemical water-splitting cycles of chlorine family for hydrogen production. Energ Conver Manage 2022;271: 116313.

[5] Özdemir A, Genç G. A comprehensive comparative energy and exergy analysis in solar based hydrogen production systems. Int J Hydrogen Energy 2022;47: 12189–203.

[6] Asal Ş, Acır A. A study on nuclear hydrogen production using a novel approach cobalt-chlorine thermochemical cycle in a laser driver fission fusion blanket for various molten salt fuels. Progress in Nuclear Energy 2022;153:104443.

[7] Juárez-Martínez L C, Espinosa-Paredes G, Vázquez-Rodríguez A, Romero-Paredes H. Energy optimization of a Sulfur–Iodine thermochemical nuclear hydrogen production cycle. Nuclear Engineering and Technology 2021;53:2066-2073.

[8] Özkaya M, Acır A, Yalçın Ş. Investigation of the hydrogen production of the PACER fusion blanket integrated with Fe–Cl thermochemical water splitting cycle. Nuclear Engineering and Technology 2023;55:4287-4294.

[9] Asal Ş. and Acır A., ''Utilization of the Cu–Cl thermochemical cycle for hydrogen production using a laser driver thorium molten salts'' International Journal of Hydrogen Energy 2021;46:31133-31142.

[10] Demir N. Hydrogen production via steam-methane reforming in a SOMBRERO fusion breeder with ceramic fuel particles. International Journal of Hydrogen Energy 2013;38:853–860.

[11] Acır A., Özkaya M., Performance evaluation of the Fe–Cl and Mg–Cl cycle for hydrogen production of the minor actinide fuelled PACER fusion blanket, International Journal of Hydrogen Energy, 67, 2024, 634-643.

[12] Genç G. Hydrogen production potential of APEX fusion transmuter fueled minor actinide fluoride. International Journal of Hydrogen Energy 2010;35:10190–10201.

[13] Balta M T, Dincer I, Hepbasli A. Energy and exergy analyses of magnesium-chlorine (Mg-Cl) thermochemical cycle. International Journal of Hydrogen Energy 2012;37:4855-4862.

[14] Asal, Ş., Acır A., Dinçer İ., A study on integrated HTR-PM driven hydrogen production using thermochemical cycles, Energy Conversion and Management, 307, 2024, 118336

[15] S. Reyes, J. F. Latkowski, J. Sanz, and J. Gomez del Rio, Safety Assessment for Inertial Fusion Energy Power Plants: Methodology and Application to the Analysis of the HYLIFE-II and SOMBRERO Conceptual Designs, Journal of Fusion Energy, Vol. 20, Nos. 1/2, June 2001

[16] M. Tolga Balta, Ibrahim Dincer, Arif Hepbasli Performance assessment of solar-driven integrated Mg–Cl cycle for hydrogen production, International Journal of Hydrogen Energy, 39 (35), 2014, 20652-20661

[17] Özcan H, Dincer I. Performance investigation of magnesium–chloride hybrid thermochemical cycle for hydrogen production. International Journal of Hydrogen Energy 2014;39: 76-85.

[18] Çengel YA, Boles MA. Thermodynamics: an engineering approach. McGraw-Hill; 2011.

[19] NIST chemistry WebBook. 2018. http://webbook.nist.gov/ chemistry/.

[20] Briesmeister JF. A General Monte Carlo N-Particle Transport Code. LA-13709M. Los Alamos National Laboratory: MCNP; 2000

[21] Acır A., Özkaya M., Performance evaluation of the Fe–Cl and Mg–Cl cycle for hydrogen production of the minor actinide fuelled PACER fusion blanket, International Journal of Hydrogen Energy, 67, 2024, 634-643.