Conceptual Core Design and Application of Mobile Symmetrically Inserted Heat-Pipe-Cooled Traveling Wave Reactor

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Abstract

Heat pipe reactors use heat pipe for passive cooling and are highly suitable for the energy supply of decentralized markets. Traditional mobile heat pipe reactors have smaller power level and cannot satisfy the higher power requirement of decentralized areas. Mobile heat pipe cooled traveling wave reactor (HPTWR), which uses neutron traveling wave to realize the long-term operation, is an excellent candidate for decentralized markets. In the present work, a radial traveling wave technology and a symmetrical inserted heat pipe technology are applied in the HPTWR core and a mobile symmetrical inserted heat pipe cooled traveling wave reactor (SI-HPTWR) core is developed. The radial traveling wave technology can improve the breeding capability of core and reduce the radial power peaking factor of core. Besides, the symmetrical inserted heat pipe technology can effectively reduce the maximum core temperature. The 60 MWth SI-HPTWR is capable of supporting an around 60-year operation. Compared with other traditional reactors, SI-HPTWR has the higher safety, better mobility and economic benefits in the electricity market and heat utilization of decentralized areas.

Full Text

Preamble

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Abstract: Heat pipe reactors utilize heat pipes for passive cooling and are highly suitable for energy supply in decentralized markets. Traditional mobile heat pipe reactors have relatively low power levels that cannot meet the higher power demands of larger decentralized areas. The mobile heat pipe cooled traveling wave reactor (HPTWR), which employs a neutron traveling wave to achieve long-term operation, represents an excellent candidate for decentralized markets. In this work, radial traveling wave technology and symmetrical inserted heat pipe technology are applied to the HPTWR core, resulting in the development of a mobile symmetrical inserted heat pipe cooled traveling wave reactor (SI-HPTWR) core. The radial traveling wave technology can improve core breeding capability while reducing the radial power peaking factor. Additionally, the symmetrical inserted heat pipe technology can effectively reduce the maximum core temperature. The 60 MWth SI-HPTWR is capable of supporting approximately 60 years of operation. Compared with traditional reactors, the SI-HPTWR offers higher safety, better mobility, and greater economic benefits for electricity markets and heat utilization in decentralized areas.

Keywords: Heat pipe reactor; Traveling wave reactor; Neutronics analysis; Thermal analysis; Economic benefits

Introduction

As global energy demands increase alongside growing threats from climate change, many countries have intensified their efforts to develop nuclear energy [1]. In recent years, due to the high capital costs of traditional large commercial nuclear power plants and the need to supply electricity to small grids in decentralized areas, a trend has emerged toward developing small nuclear reactor units [2]. Among various nuclear reactor designs, Small Modular Reactors (SMRs) with capacities below 300 MWe are particularly suitable for decentralized areas such as space exploration sites, remote mines, military bases, and island communities [3]. Unlike traditional large commercial nuclear power plants, SMR components can be fabricated in factory settings and then transported as modules to remote locations for installation. Consequently, the total cost of SMRs is substantially reduced through factory fabrication, short construction times, and standardization for commercial deployment, making them competitive in the energy markets of decentralized areas [4-5]. The Strategic Insights report [6-7] projects significant future demand for SMRs, identifying China and the United States as the most promising markets, with projected new SMR additions of 5 GWe in China and between 1 and 5 GWe in the United States by 2035 [7].

Over the past two decades, numerous SMR designs have been developed, primarily including water-cooled reactors [8-9], gas-cooled reactors [10], liquid-metal cooled reactors [11], molten salt cooled reactors [12-13], and heat pipe cooled reactors [14]. Due to their higher power density, simpler construction, lower manufacturing costs, and enhanced safety, heat pipe reactors are exceptionally well-suited for energy supply in decentralized areas [14-16]. The heat pipe reactor was originally developed for space exploration projects in the 1960s [17]. Because of limited rocket transportation capacity and high power requirements for space exploration, the mass of heat pipe reactor systems was designed to be as small as possible while maximizing power output [18]. Recently, various small modular heat pipe reactors have been proposed for terrestrial decentralized applications. Los Alamos National Laboratory (LANL) developed the MegaPower reactor, whose core consists primarily of 6 monolith blocks, 2112 fuel pins, 1224 heat pipes (HPs), and radial and axial reflectors [19]. This reactor can supply 5 MWth for 12 years, with core radius and height of only 77.85 cm and 200 cm respectively, enabling easy deployment by truck. To improve core power level and lifetime, Choi [20] optimized the HP diameter and core structure, developing an 18 MWth hybrid micro modular reactor (HMMR) composed of 18 fuel assemblies with radial and axial reflectors. The equivalent core radius and height are 102.5 cm and 280 cm respectively, and the solid core with 12% enriched UN fuel can continuously supply power for a full-system lifetime of 56 years. Subsequently, Westinghouse developed the eVinci heat pipe reactor with 15 MWe capacity for off-grid market energy supply in 2018 [21]. A symmetrical-ended HP design (with cooled zones on both sides of a single heated zone) was applied to the core to improve heat transport limits compared to single-ended HPs. The core with UO_2 fuel (19.75% ^{235}U enrichment) has the potential to operate for up to 10 years. To further increase core power level, a 125 MWth Heat Pipe Encapsulated Nuclear Heat Source (HP-ENHS) reactor was developed by inserting two symmetrical independent HPs in each coolant channel [22], with core radius and axial length of 97.2 cm and 400 cm respectively.

However, both the HP-ENHS and HMMR cores have very large volumes and masses that cannot be deployed by truck or airplane.

To meet the higher energy demands of decentralized areas, advanced heat pipe reactors require two key characteristics: mobility and higher power levels. While many heat pipe reactors can be transported by truck or airplane, their power levels are relatively low (less than 50 MWth), which cannot satisfy the power requirements of large decentralized areas. For example, remote mining applications demand approximately 20 MWe, equivalent to about 57 MWth assuming 35% thermoelectric conversion efficiency [23-24]. Therefore, higher heat transport HP and axial traveling wave technologies have been applied to heat pipe reactors, resulting in the development of a 70 MWth heat pipe cooled traveling wave reactor (HPTWR) core in previous studies [25-26]. The maximum HP and fuel temperatures in the HPTWR core are approximately 1800 K and 2394 K respectively [26]. To reduce the maximum core temperature, symmetrical inserted HP technology will also be applied to the HPTWR core, leading to the development of a symmetrical inserted heat pipe cooled traveling wave reactor (SI-HPTWR) core. To improve breeding capability and reduce the radial power peaking factor (PPF), the SI-HPTWR core will be segmented radially into two fuel regions, introducing a radial traveling wave. The lifetime, breeding capability, and fuel and HP temperatures of the SI-HPTWR core will be analyzed. Section 2 describes the geometry model and computational tools, results are presented in Section 3, applications and advantages are discussed in Section 4, and conclusions are provided in Section 5.

2.1 Core Model

[Figure 1: see original paper] Radial and longitudinal layouts of SI-HPTWR core.

[Figure 2: see original paper] Radial FE loading of one-sixth core for SI-HPTWR.

The radial and longitudinal layouts of the 60 MWth SI-HPTWR core are shown in Fig.1 [26]. The core features an independent central HP fuel element (FE) design, radially composed of 1008 FEs. To enable propagation of both axial and radial traveling waves, the core is segmented axially and radially into two fuel regions respectively. The axial lengths of the axial ignition fuel region (IFR) and breeding fuel region (BFR) are 30 cm and 70 cm respectively. The numbers of FEs in the radial inner and outer fuel regions are 450 and 558 respectively. To reduce the core PPF, radial ignition fuel and breeding fuel are loaded into the radial outer and inner fuel regions respectively. The radial FE loading for one-sixth of the SI-HPTWR core is shown in Fig.2. The lattice half-pitch of each FE is 1.7128 cm, and each FE is inserted with two independent HPs from both axial sides (left and right). The Li HPs in the SI-HPTWR core must be replaced during the entire cycle length due to their relatively shorter lifetime [20]. Based on the core thermal power and number of HPs, the average HP temperature is approximately 1520 K. The corresponding vapor and liquid densities of Li in the HP gas channel and liquid annulus are approximately 3×10^{-5} g/cm^3 and 0.414 g/cm^3 respectively [27-28]. The specific parameters of FEs and HPs are listed in a previous study [26]. The 1008 FEs in the core contain 2016 HPs, which are surrounded by radial and axial reflectors and a vessel. The core radius and axial length are 90.3 cm and 130 cm respectively. The mass of the SI-HPTWR core is approximately 29.04 tons (14.87 tons of fuel, 5.1 tons of cladding, 0.47 tons of HPs, 7.65 tons of reflector, and 0.95 tons of vessel), enabling easy transportation by truck or airplane. Table 1 tabulates the design parameters of the SI-HPTWR core.

[Figure 3: see original paper] Nuclear system schematic of SI-HPTWR.

Each coolant channel in the core is inserted with two symmetrical independent HPs along both axial directions. The number of HPs in the SI-HPTWR core is double that in the HPTWR core with single inserted HPs [26]. Because the axial length of the HP evaporation section in the core is shortened, HP irradiation damage in the SI-HPTWR core will be reduced relative to the HPTWR core for the same irradiation time. Therefore, the Li HPs in the SI-HPTWR core can achieve a longer lifetime, reducing the replacement frequency of failed HPs and improving core economics and safety.

Table 1: Design Parameters of SI-HPTWR Core

Parameters	Value
Thermal power	60 MWth
FEs amounts	1008
Density of UN fuel	13.59 g/cm^3
^{15}N enrichment in UN fuel	99.9%
Thermal conductivity of UN at 1700 K [29]	24 W/(m · K)
Axial length of fuel	100 cm
Mass of heavy nuclides	12.11 t
Density of Mo-14Re cladding	12 g/cm^3
Thermal conductivity of Mo-14Re at 1700 K [30]	2 W/(m · K)
HPs amounts	2016
^{7}Li enrichment in Li HP	99.9%
Density of liquid Li in HP [27-28]	0.414 g/cm^3
Density of vapor Li in HP [27-28]	3$×10^{-5}$ g/cm^3
Density of Al_2O_3 reflector	3.9 g/cm^3
Outer radius of reflector	90.3 cm
Axial length of reflector	15 cm
Density of B_4C vessel	2.52 g/cm^3
^{10}B enrichment in B_4C vessel	99.9%

2.2 Computational Tool

In this work, the Monte Carlo code RMC with the ENDF/B-VII cross-section library is used to perform neutronic calculations. RMC is a code program developed by the REAL team for neutron-photon-electron transport simulation [31-32]. The depletion simulations employ 30,000 neutrons per history with 400 batches and 50 discarded batches, resulting in a standard deviation of k_{eff} below 20 pcm for every depletion step. Both the SI-HPTWR and HPTWR cores are set at 60 MWth. Fuel and HP temperatures for both cores in neutronics calculations are set at 1700 K to simplify calculations based on the average UN temperature of 1700 K (see Section 4). To examine the axial power profile, fuel regions in both cores are segmented axially into 20 small depletion zones, each with an axial length of 5 cm.

HP thermal calculations for the SI-HPTWR and HPTWR cores are performed using the thermal resistance-capacitance network model (TreCan), which has been verified in a previous study [26]. The HP evaporation section is segmented axially into 10 small zones because its axial length is half that of the total fuel region. The axial FE power distribution serves as the heat source in HP thermal calculations. The HP condensation section is cooled by liquid metal Li, with temperature and velocity set at 1470 K and 0.3 m/s respectively.

For liquid Li cooling an axial cylinder with Reynolds numbers (Re) between 10^4 and 10^5, the Nusselt number (Nu) is calculated through the correlation Nu

= 8 + 0.002 × Re [33]. Based on Newton' s cooling law, the heat transport of liquid Li in the HP condensation sections can be represented by $Q = h \times A \times (T_w - T_c)$, where h is the heat transfer coefficient, A is the surface area of the HP condensation section, T_w is the surface temperature of the HP condensation section, and T_c is the temperature of the intermediate coolant. The axial lengths of the HP adiabatic and condensation sections are set at 0.35 m and 1.0 m respectively. The HP evaporation section in the SI-HPTWR core is shortened to 0.5 m due to the application of symmetrical inserted HP technology. Formulations for Li HP heat transport limits can be found in a previous study [26].

3. Results

3.1 U-Pu Breeding

In a previous study, we analyzed the neutronic and thermal characteristics of the HPTWR core [26]. Unlike the HPTWR core, the SI-HPTWR employs symmetrical inserted HP technology and is segmented radially into two fuel regions. To demonstrate the effects of symmetrical inserted HP and radial traveling wave technologies on core reactivity, the initial k_{eff} values for both HPTWR and SI-HPTWR cores were set at approximately 1.0000 by adjusting the ^{235}U enrichments in each fuel region. Table 2 shows the ^{235}U enrichments of UN fuel for each region in the HPTWR and SI-HPTWR cores. Both cores have identical materials, geometries, and power levels. The radial outer IFR in the SI-HPTWR core experiences greater neutron leakage than the HPTWR core due to its higher ^{235}U enrichment. Consequently, the average ^{235}U enrichment (11.5%) in the SI-HPTWR core is slightly higher than that in the HPTWR core (11.1%). Figure 4 shows the k_{eff} changes versus operation time for both cores. Due to breeding in the breeding fuel, the positive reactivity inserted by newly generated fissile isotopes exceeds the negative reactivity from fuel consumption and fission product accumulation during the early cycle length [34]. Therefore, the k_{eff} of the SI-HPTWR core initially increases, then gradually decreases due to declining ^{235}U and ^{238}U inventories. The maximum k_{eff} of the SI-HPTWR core is approximately 1.0082 during the cycle length, higher than the HPTWR core' s maximum k_{eff} (approximately 1.0066) because the radial breeding wave applied in the SI-HPTWR core (see Fig.7) improves breeding capability (see Fig.5). The SI-HPTWR core can operate for approximately 60 effective full power years, exceeding the HPTWR core' s lifetime of about 54 years. The k_{eff} swing range for the SI-HPTWR core (approximately 0.82%) remains below 1% throughout the entire cycle length.

Table 2: ^{235}U Enrichments of UN Fuel for Each Region in HPTWR and SI-HPTWR Cores

Region	SI-HPTWR	HPTWR
Axial IFR	13.83%	13.22%
Axial BFR	9.93%	9.32%
Radial inner fuel region	9.32%	11.22%
Radial outer fuel region	15.12%	11.22%

[Figure 4: see original paper] Changes of k_{eff} for SI-HPTWR and HPTWR cores during cycle length.

Nuclear fuel inventories in the reactor core continuously decrease while new fissile Pu isotopes accumulate during the U-Pu fuel cycle. Figure 5(a) shows the ^{235}U inventories and consumption in the SI-HPTWR and HPTWR cores during the cycle length. Due to its higher average ^{235}U enrichment, the SI-HPTWR core has a higher initial ^{235}U inventory than the HPTWR core (approximately 1.38 t versus 1.33 t at beginning of cycle (BOC)). Inventories of newly bred fissile Pu isotopes gradually increase in both cores (see Fig.5(b)), inserting positive reactivity. Consequently, the consumption rates of ^{235}U gradually decrease in both cores during the cycle length. The SI-HPTWR core exhibits slightly higher ^{235}U consumption than the HPTWR core at the same operation time due to its higher initial inventory. At end of cycle (EOC), ^{235}U inventories are approximately 0.49 t and 0.51 t in the SI-HPTWR and HPTWR cores respectively, with corresponding consumptions of approximately 0.89 t and 0.82 t.

Figure 5(b) shows the ^{238}U consumption and ^{239}Pu and ^{241}Pu production in both cores during the cycle length. At EOC, ^{238}U consumptions are approximately 1.42 t and 1.31 t in the SI-HPTWR and HPTWR cores respectively, with corresponding ^{239}Pu productions of approximately 0.69 t and 0.66 t. The corresponding ^{241}Pu productions are approximately 3.1 kg and 2.76 kg respectively at EOC. The production rates of ^{239}Pu and ^{241}Pu in both cores gradually increase and decrease respectively during the cycle length because ^{238}U and ^{239}Pu inventories decrease and increase respectively.

The ^{238}U consumption and ^{239}Pu and ^{241}Pu production in the SI-HPTWR core are lower than those in the HPTWR core at the same operation time because the SI-HPTWR core has a lower ^{238}U loading mass at BOC. However, the ^{235}U consumption, ^{238}U consumption, and ^{239}Pu and ^{241}Pu production in the SI-HPTWR core during the entire cycle length are higher than those in the HPTWR core because the SI-HPTWR core has a longer lifetime. To assess U-Pu fuel cycle breeding capability, the production fraction (PF) of fissile Pu isotopes is evaluated by:

$$PF = \frac{Pu_{239} + Pu_{241}}{U_{238}^{BOC}} \times 100\%$$

where Pu_{239} and Pu_{241} refer to ^{239}Pu and ^{241}Pu productions at EOC, and U_{238}^{BOC} refers to the ^{238}U inventory at BOC. The PF of the SI-HPTWR core is approximately 6.46%, slightly higher than the HPTWR core' s PF (6.15%) during the entire cycle length due to its superior U-Pu breeding capability (also evidenced by the higher k_{eff} swing range in Fig.4). The nuclear fuel burnup in the SI-HPTWR core is approximately 108.33 GWd/MTU at EOC, slightly higher than the HPTWR core' s burnup (98.42 GWd/MTU).

3.2 Power Distribution

The SI-HPTWR core features two axial and two radial fuel regions. The IFR with higher ^{235}U enrichment leaks more fission neutrons to the BFR during the cycle length, while the BFR with lower ^{235}U enrichment has a higher ^{238}U inventory, enabling greater ^{238}U breeding.

Burning of ignition fuel and breeding of breeding fuel in the SI-HPTWR core lead to changes in axial and radial power profiles during the cycle length. Figure 6 shows the axial power profile changes for the SI-HPTWR core (a) and HPTWR core (b) during the cycle length. Both cores have identical power levels and fuel enrichment differences between axial IFR and BFR, resulting in similar axial power profile changes. The SI-HPTWR core' s axial peak power (approximately 5.38 MWth) is slightly lower than the HPTWR core's peak (5.46 MWth) at BOC because the axial reflector along the axial IFR direction in the SI-HPTWR core is also inserted with HPs, causing greater neutron leakage. Due to consumption of axial ignition fuel and breeding of axial breeding fuel, the axial peak powers decrease to approximately 3.76 MWth and 3.77 MWth at EOC for the SI-HPTWR and HPTWR cores respectively. The SI-HPTWR core has a lower axial peak power at EOC relative to the HPTWR core due to its longer lifetime. Both cores maintain the same axial peak positions at BOC and EOC (approximately 22.5 cm and 47.5 cm respectively). The axial traveling wave speeds in the SI-HPTWR and HPTWR cores are approximately 0.4167 cm/year and 0.4630 cm/year respectively during the entire cycle length.

Unlike the HPTWR core with uniform radial fuel enrichment, the SI-HPTWR core has two radial fuel regions with different enrichments. To explore radial traveling wave characteristics, Fig.7(a) and (b) show the radial normalized power profiles of one-sixth of the SI-HPTWR core at BOC and EOC respectively. Because radial IFR and BFR are loaded into the radial outer and inner core positions respectively, the FE in the radial IFR near the radial BFR position has the maximum power distribution at BOC. The maximum power FE is No. 92, located 43.11 cm from the core center, with a corresponding radial PPF of approximately 1.118 and maximum FE power of 66.55 kWth. FEs near the radial reflector position have relatively higher power distributions at BOC because more thermal neutrons are reflected by the radial reflector and ^{235}U has a larger thermal neutron fission cross-section. Consequently, FE power distributions in the radial outer IFRs first decrease then increase with increasing core radius. More fission neutrons in the radial outer fuel region diffuse to the radial inner fuel region during early cycle length and leak to the radial reflector throughout the cycle length due to the relatively higher power distribution. More ^{238}U in the radial inner fuel region is bred into Pu isotopes, while more ^{235}U in the radial outer fuel region is consumed during the cycle length due to higher neutron leakage. Therefore, FE power distributions in the radial inner and outer fuel regions gradually decrease and increase respectively during the cycle length. Additionally, neutrons leaking to the radial reflector in the SI-HPTWR core gradually decrease during the cycle length due to decreasing power distribution in radial outer FEs. The SI-HPTWR has relatively lower FE power distribution in the core center at both BOC and EOC because the core center contains a safety rod channel. The maximum power FE at EOC is No. 173, located in the radial inner fuel region. The SI-HPTWR core successfully propagates a radial traveling wave during the entire cycle length, with the radial distance between FE No. 173 and the core center being 16.57 cm. The corresponding radial traveling wave speed is approximately 0.4423 cm/year.

Figure 8 shows the axial power profile changes of the radial IFR and BFR in the SI-HPTWR core at BOC and EOC. The radial outer IFR has a higher power distribution at BOC due to its higher ^{235}U enrichment and greater number of FEs, with axial peak powers of approximately 2.80 MWth and 2.58 MWth for radial IFR and BFR respectively at BOC. Nuclear fuel in the radial outer IFR and inner BFR of the SI-HPTWR core is gradually consumed and bred respectively during the cycle length, resulting in higher power distribution in the radial inner fuel region than the outer region at EOC. The axial peak powers decrease to approximately 1.71 MWth and 2.06 MWth for radial IFR and BFR respectively at EOC.

The normalized PPF and corresponding FE power in the SI-HPTWR and HPTWR cores are shown in Fig.9 during the cycle length. The SI-HPTWR core's PPF is reduced to approximately 1.118 at BOC compared to the HPTWR core (approximately 1.36) because the core is segmented radially into two fuel regions. The PPF increases to approximately 1.327 at 50 years due to breeding in the radial inner fuel region. After 50 years, much of the nuclear fuel in the radial inner breeding region has been consumed, causing the normalized PPF to decrease to approximately 1.322 at 60 years. The corresponding FE power increases from approximately 66.55 kWth at BOC to approximately 79.02 kWth at around 50 years, then decreases to approximately 78.67 kWth at EOC. The SI-HPTWR core' s PPF remains lower than that of the HPTWR core throughout the entire cycle length, demonstrating that radial traveling wave technology can reduce the PPF of heat pipe reactor cores.

Figure 10 shows the axial power profile changes of the maximum power FE in the SI-HPTWR core during the cycle length. The axial power profiles of the maximum power FE are similar to those of the core (see Fig.6(a)). The axial peak power of the maximum power FE decreases from approximately 6.02 kWth at BOC to approximately 5.04 kWth at EOC, with axial positions of 27.5 cm and 52.5 cm respectively. The axial traveling wave speed of the maximum power

FE is consistent with that of the core power profiles.

3.3 Temperature Distribution

The symmetrical inserted HP technology increases the number of HPs in the heat pipe reactor, while the radial traveling wave technology reduces the radial normalized PPF during the cycle length. To study the effects of increased HP numbers and decreased radial normalized PPF on core temperature, thermal calculations of Li HPs and UN fuel are performed using the TreCan code and Fluent for the SI-HPTWR and HPTWR cores respectively [35].

Each FE in the SI-HPTWR core has two axially symmetrical inserted HPs compared to the single inserted HP in the HPTWR core. To simplify heat calculations, the junction of the two axially symmetrical inserted HPs in one FE is treated as adiabatic. Figures 11(a) and (b) show the axial HP wall temperature profile changes in the maximum power FE of the SI-HPTWR and HPTWR cores during the cycle length respectively. For the SI-HPTWR core, the HP wall peak temperature is approximately 1596.17 K at BOC, located at 27.5 cm. The axial HP wall temperature profiles in the axial IFR and BFR directions gradually decrease and increase respectively during the cycle length because the corresponding axial FE power profiles decrease and increase respectively (see Fig.10). The HP wall peak temperature decreases to approximately 1579.53 K at EOC, with its axial position shifting to 47.5 cm. The peak temperature axial position in the maximum power FE propagates from the axial IFR at BOC to the axial BFR at EOC. The HP wall peak temperature along the axial BFR direction in the maximum power FE increases from approximately 1526.24 K at BOC to approximately 1574.68 K at EOC, always remaining at 52.5 cm during the entire cycle length. HP wall peak temperatures along the axial BFR direction are always lower than those along the axial IFR direction throughout the cycle length.

Because the junction of the two axially symmetrical inserted HPs is located at the core midplane, the HP wall experiences a larger temperature difference at this axial junction. This temperature difference decreases from approximately 51.84 K at BOC to approximately 1.43 K at EOC due to axial power profile flattening during the cycle length. For the HPTWR core, the HP wall peak temperature decreases from approximately 1658.45 K at BOC to approximately 1645.70 K at EOC.

To evaluate the heat transport capability of symmetrical inserted HP technology, Fig.12 shows the HP wall peak temperatures in the maximum power FE for both SI-HPTWR and HPTWR cores, along with the corresponding temperature differences. The HP wall peak temperature in the SI-HPTWR core is always lower than that in the HPTWR core during the cycle length, with the peak temperature difference increasing from approximately 62.50 K at BOC to approximately 67.50 K at around 50 years. The average FE power and small fuel zone power in the SI-HPTWR core are approximately 59.52 kWth and 2.976 kWth respectively. The average HP wall temperature in the SI-HPTWR core is reduced to approximately 1544.4 K compared to the HPTWR core (approximately 1594.4 K) due to symmetrical inserted heat pipe technology. The maximum HP wall temperature in the SI-HPTWR core gradually decreases during the cycle length, effectively enhancing reactor safety.

Based on the maximum power FE, HP heat transport limits must be assessed to ensure core heat transport throughout the cycle length. Figure 13(a) shows HP vapor temperatures and corresponding heat transport limits in the maximum power FE of the SI-HPTWR core during the cycle length. Figure 13(b) shows HP heat transport margins and corresponding margin differences in the maximum power FE of the SI-HPTWR and HPTWR cores during the cycle length. The FE thermal power in the SI-HPTWR core is distributed between two inserted HPs, with only half the axial FE thermal power transported by each HP. HP vapor temperature increases with transported thermal power, while the corresponding HP heat transport margin exhibits opposite trends. Therefore, HP vapor temperatures along the axial IFR and BFR directions decrease and increase respectively from approximately 1553.6 K and 1504.5 K at BOC to approximately 1540.6 K and 1538.9 K at EOC. The corresponding heat transport limits decrease and increase respectively from approximately 77.76 kWth and 55.44 kWth at BOC to approximately 71.28 kWth and 70.47 kWth at EOC. The corresponding heat transport margins increase and decrease respectively from approximately 38.66% and 66.01% at BOC to approximately 44.08% and 44.93% at EOC. Due to peak power reduction, the minimum HP heat transport margins in the SI-HPTWR core gradually increase during the cycle length and remain higher than those in the HPTWR core. The HP heat transport margin difference in the maximum power FE between SI-HPTWR and HPTWR cores increases from approximately 28.69% at BOC to approximately 34.12% at 50 years. Therefore, symmetrical inserted HP technology and radial traveling wave technology can effectively enhance HP heat transport margins in heat pipe cooled traveling wave reactor cores.

UN fuel temperatures in the SI-HPTWR and HPTWR cores are also assessed. Based on core neutronics and HP thermal calculations, the small fuel zones with maximum and average powers in both cores are modeled with adiabatic boundaries at the outer surface of the small fuel zone to simplify calculations. Heat transport through gas gaps in FEs is negligible due to their very small thickness [36]. Mesh sensitivity analysis for the small fuel zone was assessed in a previous study [26]. The maximum fuel temperature in the maximum power FE of the SI-HPTWR core is first evaluated. Figure 14 shows the radial (a) and axial (b) temperature profiles of the maximum power small fuel zone in the SI-HPTWR core at BOC. Because the central HP is surrounded by radial fuel, fuel temperature gradually decreases with decreasing FE radius. The axial fuel temperature profile remains essentially unchanged because the small fuel zone axial length is only 5 cm and UN fuel has high thermal conductivity. The maximum fuel temperature is approximately 2024 K at BOC [37].

Figure 15 shows the maximum fuel temperatures in the HPTWR and SI-HPTWR cores, along with corresponding temperature differences during the cycle length. The maximum fuel temperature in the SI-HPTWR core decreases to approximately 1925 K at EOC, with the decreasing rate gradually diminishing because the maximum fuel zone power gradually decreases during the cycle length. Based on the average small fuel zone power (2.79 kWth) and corresponding HP wall temperature (1544.5 K), the average fuel temperature in the SI-HPTWR core is approximately 1700 K, lower than the average temperature (approximately 1750 K) in the HPTWR core. Maximum fuel temperatures in the SI-HPTWR core remain lower than those in the HPTWR core throughout the entire cycle length, with the temperature difference decreasing from approximately 240 K at BOC to approximately 78 K at 50 years. Symmetrical inserted HP technology and radial traveling wave technology can effectively reduce maximum fuel temperatures during the cycle length.

4. Discussion

Symmetrical inserted HP technology and radial traveling wave technology in heat pipe reactors can effectively improve core safety. The mobile SI-HPTWR can achieve 60 MWth power output with 60 years of continuous operation, offering numerous advantages over traditional reactors in decentralized areas.

4.1 Safety of SI-HPTWR

The power system volumes for water, gas, liquid metal, and molten salt cooled reactors are very large, with long construction cycles and high costs that many small manufacturers cannot sustain. HP usage in reactors shrinks power system volume, representing a key enabler for reducing construction costs and investment risks. The SI-HPTWR does not require main pipelines, circulating pumps, or auxiliary systems compared to traditional reactors with liquid or gas coolants, resulting in a compact system. Therefore, loss-of-coolant accidents and high-pressure piping ruptures do not occur in the SI-HPTWR during the cycle length. Additionally, the high mobility of SI-HPTWR can potentially simplify siting factory requirements and engineering tasks. The SI-HPTWR can be easily installed underground via truck transportation, further improving security through natural isolation of the containment area from external disruptors and releases. During serious accidents, the SI-HPTWR power system can be rapidly transported to a safe region by truck or airplane, reducing maximum radiological hazards to the environment and human health.

4.2 Application of SI-HPTWR

The SI-HPTWR can support both household loads and industrial demands on Earth, with two primary application fields in decentralized areas: electricity markets and heat utilization.

(a) Electricity Market

The levelized unit electricity cost of diesel in remote communities ranges from $0.466/kWh - $0.487/kWh in Canada, comprising capital, operating, and decommissioning costs [38]. SMRs could provide an economically viable solution for delivering clean energy in decentralized electrical markets. The levelized unit electricity cost for a 10 MWe light water reactor has been estimated at approximately $0.453/kWh (2015 US dollars) [1]. Relative to other SMRs with liquid or gas coolant, the devices of power system of SI-HPTWR are smaller and the corresponding construction cycle will be shorted, which would further reduce the levelized unit electricity cost. The requirements of plant location for the SI-HPTWR are much less than those for other SMRs due to its high mobility. The SI-HPTWR can be transported at any time according to the need and the construction cost will be saved for the smaller electrical grids. Relative to the small grid with long distance transmission, the power disruptions during contingencies can be minimized or avoided by maintaining the continuous operation of SI-HPTWR. Besides, the application of SI-HPTWR in the decentralized areas can also eliminate the power transmission losses and provide increased resiliency.

Due to the flexible siting attributes and firming power generation, the SI-HPTWR can also integrate with variable renewable energy to balance energy demands, and thus compensate the instability of wind, solar power and follow load. The power reserve requirements can be reduced by the application of SI-HPTWR, which can also provide the economic benefits in the decentralized areas. (b) Heat utilization The heat utilization in the decentralized areas mainly is composed of the process heat and district heating.

The process heat with temperature ranging from 573 K to 1123 K are very common in a variety of industries (such as chemical and plastics manufacturing, food processing, petroleum refining, and hydrogen production and so on) [39]. By participating in wholesale power markets, 113 facility processes with 33.9 GWth/year thermal demand could be economically served by SMRs at 2021 US, which could avoid 4 million tons of CO2 emissions per year [40]. The intermediate coolant temperature in the heat exchange of SI-HPTWR is 1470 K during the cycle length, which has a very high producing heat rate and is a suitable choice. Besides, the waste heat from nuclear generation (40-60 ℃) can be also applied to district heating systems, which increases the overall thermal efficiency of the plant and provides another revenue stream aside from electricity. District heating systems has a large market, which account for approximately 6% of global heat consumption [40]. For example, district heating systems supplies currently over 200 million persons in China and Russia [41]. In 2019, the market sizes of district heating in Europe and the Whole World were USD$0.137-0.173/kWh [39]. The SI-HPTWR can supply both electricity and heat simultaneously, offering greater economic benefits than reactors providing only electricity. The levelized unit heat cost of SMRs for district heating is approximately 0.03-0.05 $/kWh [40-41], significantly lower than the levelized unit heat cost of natural gas (0.06-0.08 $/kWh) [42]. Therefore, the SI-HPTWR can provide more economical heat supply for district heating in decentralized areas.

(b) Heat Utilization
District heating is an effective method for decarbonizing the heat sector [40]. However, network modifications present a major challenge for implementing nuclear-fueled district heating systems. In some regions, network modification costs exceed 10 million Euros per kilometer, limiting the application of conventional nuclear facilities located far from dense population centers [43]. When mobile SI-HPTWR is deployed, the distance piping network can be significantly shortened, saving substantial transmission network costs.

5. Conclusion

Based on the heat pipe cooled traveling wave reactor, symmetrical inserted HP and radial traveling wave technologies are applied to the core to reduce maximum core temperature and improve breeding capability. The conclusions are as follows:

1. The lifetime of the 60 MWth SI-HPTWR is approximately 60 years. The ^{239}Pu and ^{241}Pu productions and fissile isotope production fraction in the core are approximately 0.69 t, 3.1 kg, and 6.46% respectively during the entire cycle length. Radial traveling wave technology can improve core breeding capability.
2. The core can realize propagation of both axial and radial traveling waves during the entire cycle length, with corresponding traveling wave speeds of approximately 0.4167 cm/year and 0.4423 cm/year respectively. Radial traveling wave technology can decrease the radial PPF of the core.
3. The maximum HP wall and fuel temperatures in the SI-HPTWR core are approximately 1579.53 K and 1925 K respectively at EOC. Symmetrical inserted HP and radial traveling wave technologies can effectively reduce maximum core temperature.

The SI-HPTWR offers excellent mobility and can provide economical service for electricity markets and heat utilization in decentralized areas.

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