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TOPICAL REVIEW

Small Modular Reactors: An Overview of Modeling, Control, Simulation, and Applications

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ABSTRACT A small modular reactor (SMR) is a nuclear reactor that is characterized by its smaller size and capacity when compared to traditional large-scale nuclear reactors. An SMR is often categorized as having an electrical output of less than 300MW and is built to be more mobile, safe, and extensible to deploy. It has been established that SMRs can provide economic and flexibility advantages in a variety of industries thanks to the development, study, and use of multiple types of SMRs in recent years. The goal of this paper is to present a comprehensive overview of several SMR types, including light water reactors (LWRs), liquid metal-cooled reactors (LMRs), molten salt reactors (MSRs), and gas-cooled reactors (GCRs). Each type of reactor is reviewed in terms of its structural design, modeling control implementation, applications, and impacts concerning the power system.

INDEX TERMS Boiling water reactor, computational fluid dynamics, digital simulation, dynamic matrix controller, gas-cooled reactor, light water reactor, liquid metal-cooled reactor, mathematical modeling, molten salt breeder reactor, molten salt reactor, nuclear power, power system control, pressurized water reactor, reactor applications, reactor control, reactor design, small modular reactors, sodium-cooled fast reactor, reactor control, very high-temperature reactor.

LIST OF ABBREVIATIONS

BWR	Boiling water reactor.
CDA	Core disruptive accident.
CFD	Computational fluid dynamics.
DFR	Dual fluid reactor.
DMC	Dynamic matrix controller.
DMSR	Denatured molten salt reactor.
DNP	Delayed neutron presursor.
EPR	Experimental power reactor.
FDM	Finite difference method.
FEM	Finite element method.
FHR	Fluoride salt-cooled high-temperature reactor.
GCR	Gas-cooled reactor.
GT-MHR	Gas turbine modular helium reactor.
HTGR	High-temperature gas-cooled reactor.
HTTR	High-temperature test reactor.
HWMSR	Heavy water-moderated molten salt reactor.
IHX	Intermediate heat exchanger.
ITMSF	International thorium molten-salt forum.
LBE	Lead-bismuth eutectic.
LMR	Liquid metal-cooled reactor.
MCFR	Molten chloride fast reactor.
mHTGR	Modular high-temperature gas-cooled reactor.
MPC	Model predictive control.
MPM	Multi-physics modeling.
MSR	Molten salt reactor.
MSBR	Molten salt breeder reactor.

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MSFR	Molten salt fast reactor.
MSRE	Molten salt reactor experiment.
NSSS	Nuclear steam supply system.
PBR	Pebble bed reactor.
PWR	Pressurised water reactor.
RSP	Response surface method.
SFR	Sodium-cooled fast reactor.
SMC	Sliding-model control.
SMR	Small modular reactor.
SSR	Stable salt reactor.
TMSR	Thorium molten salt reactor.
TMSR-LF	Liquid-fuel thorium molten salt reactor.
VHTR	Very high-temperature reactor.

I. INTRODUCTION

SMRs have been attracting abundant interest recently as a potential way to meet the increasing energy requirements of many nations while simultaneously reducing greenhouse gas emissions. Compared with traditional nuclear power plants, they offer various advantages, including less costly capital expenses, improved safety features, and increased flexibility in terms of location and application [1]. SMRs are viewed as a promising technology that can offer a reliable and sustainable supply of electricity in view of the growing worries over climate change and the need to switch to more sustainable sources of energy [2]. As a result, both the public and private sectors are becoming increasingly interested in studying the possibilities of SMRs and creating a market for them.

SMRs come in a variety of types and subtypes, each having its own special characteristics. For instance, LWRs, which include Pressurised Water Reactors (PWRs) and Boiling Water Reactors (BWRs), employ water as a coolant and graphite as a neutron moderator. On the other hand, LMRs employ liquid metal as a coolant. Major subtypes of LMRs include sodium- and lead-cooled fast reactors (SFRs and LFRs), which use molten sodium and lead as coolants, respectively. MSRs use a liquid mixture of salts as fuel and coolant, enabling continuous and efficient fuel processing while reducing nuclear waste. Another type of SMR is the GCR, which has subtypes such as the high-temperature gas-cooled reactor (HTGR), the very high-temperature reactor (VHTR), and the pebble bed reactor (PBR) [3].

Since SMRs have been the subject of in-depth research for many years, this paper will give a general summary of the four types: LWR, LMR, MSR, and GCR. Six essential criteria, including reactor structural design, mathematical modeling, reactor control schemes, model simulations, real-world applications, and each SMR's impact on the power system, will be used to evaluate each type of reactor.

This overview paper is organized into 6 sections. Sections II to V introduce the LWR, LMR, MSR, and GCR, respectively, in terms of the six criteria. Section VI will provide a conclusion of the SMR overview with respect to the four types of reactors. A reference section is added at the end of this paper.

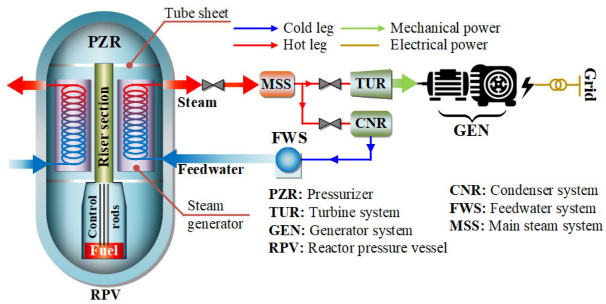

FIGURE 1. Sketch of integrated pressurized water reactor.

II. LIGHT WATER REACTOR

A. DESIGN

With the commissioning of the first nuclear-powered submarine, the USS Nautilus, equipped with a PWR reactor in 1958, it marked the beginning of an era when small nuclear reactors based on light-water designs were widely utilized in both military and civilian applications [4]. In the same year, a 60MWe PWR designed by the Westinghouse-led Bettis Naval Atomic Power Laboratory commenced commercial operation. Additionally, in 1960, the Yankee Rowe reactor (185MWe), in 1962, the Indian Point One reactor (275MWe), and the Dresden reactor (210MWe), which was designed in 1960, were also commissioned, representing a significant expansion in the deployment of nuclear power technologies [5]. The most advantageous characteristic of water coolant lies in its exceptional technical inheritability. Specifically, as a coolant, water coolant possesses extensive operational experience in applications involving temperature and pressure regulation within certain conventional devices. With regard to the safety of water coolant, it is inherently chemically non-toxic. Boron and lithium are typically introduced in the form of boric acid and lithium hydroxide for corrosion control, resulting in lesser production of tritium, which poses both biological and radiological hazards. As for the corrosion effects on device surfaces, water coolant can lead to issues such as stress corrosion cracking and fouling in stainless steel [6]. The PWR or BWR currently used in light water reactors can be easily adapted for SMR applications due to the ability to deploy system components of their primary loop within a pressure vessel. These reactors are also referred to as integral reactors. Up to the present day, more than 80% of commercial nuclear reactors worldwide have employed light water as their primary coolant, while heavy water reactors (containing deuterium instead of hydrogen) constitute a smaller proportion [7]. In this context, only LWRs will be introduced.

The design of LWRs has evolved significantly since their inception, reflecting advancements in technology and engineering over the years. In the early years of LWR development (1950s-1960s), pioneering designs like BWRs and PWRs laid the groundwork for LWR technology [8]. These early reactors were relatively small in scale and had limited power output. As technology progressed, reactors scaled up in the 1970s and 1980s. This expansion aimed to increase power output while enhancing efficiency and safety. During this period, integral PWRs and improved fuel assemblies became notable innovations [9]. In the contemporary era of LWR design (2000s-present), advanced reactor designs have taken center stage. These designs incorporate features like passive safety systems, longer fuel cycles, and advanced materials. Reactors classified as Generation III and Generation III+ reactors, such as the AP1000 and EPR, represent the latest advancements in LWR technology [10]. Designing LWRs has always presented challenges, which have spurred innovations to improve safety, efficiency, and sustainability. Safety remains a paramount concern in LWR design. Innovations include the development of passive cooling systems, advanced containment structures, and improved control mechanisms to mitigate the risk of accidents. Fuel efficiency is another crucial aspect. Advancements in this area involve the use of mixed oxide (MOX) fuel, which incorporates recycled plutonium, and the development of advanced fuel designs that extend fuel cycles [11]. Waste management is an ongoing challenge. LWR design innovations include research into advanced reprocessing techniques and long-term storage solutions to address nuclear waste disposal. Environmental impact reduction is a contemporary design goal. Innovations encompass closed-cycle cooling systems and advanced thermal-hydraulic designs to minimize water consumption and emissions.

LWRs are rooted in several fundamental principles and components. A conceptual representation of an integral LWR is shown in the Figure 1. At its core, an LWR consists of a fuel assembly, a moderator and coolant, control rods, a reactor vessel, steam generators, and a turbine-generator system [5], [12]. The fuel assembly is a central component where nuclear fission takes place. Typically, it contains fuel rods enriched with fissile material like uranium-235, which undergoes the fission process, releasing energy. Light water serves a dual purpose as both a moderator and a coolant. As a moderator, it slows down neutrons, increasing their likelihood of causing fission. Simultaneously, it functions as a coolant by carrying away the heat generated during the fission process. Control rods, made from materials like boron or cadmium, are strategically inserted into the reactor core to regulate the nuclear chain reaction. By absorbing excess neutrons, they control the reactor's power output and maintain stability. The reactor vessel is a robust containment structure that houses the reactor core, control rods, and the coolant. It must withstand extreme temperatures and pressures while ensuring the integrity of the reactor. Steam generators are crucial components that transfer heat from the reactor coolant to a secondary loop of water. This secondary loop is converted into steam, which drives turbines and ultimately generates electricity. The turbine-generator system is the final stage in the energy conversion process. Steam produced by the secondary loop drives a turbine connected to a generator, transforming mechanical energy into electrical energy.

B. MODELING

Modeling plays a pivotal role in the design, analysis, and operation of LWRs. Accurate modeling is essential for understanding reactor behavior, optimizing performance, and ensuring safety. It allows nuclear engineers and researchers to predict and assess reactor responses under various conditions without the need for costly physical experiments, which can be dangerous and resource-intensive. In the context of LWRs, modeling serves several critical purposes:

Safety Assessment: Models are instrumental in assessing reactor safety features. They provide insights into potential safety issues under various conditions, including normal operation and accident scenarios. By simulating accidents and emergencies, engineers can design robust safety protocols.

Design Optimization: Modeling helps engineers optimize reactor designs. By evaluating different configurations, fuel types, and control strategies, it is possible to achieve higher efficiency and safety. The ability to simulate and analyze performance variations is invaluable during the design phase.

Training and Education: Simulators based on LWR models are essential for training reactor operators. These simulators provide a controlled environment for operators to gain experience without posing risks to personnel or the reactor itself. They enable operators to practice emergency responses and refine their skills. Separate from simplified reactor simulators used for operator training, various modeling approaches are employed in LWR analysis, each with a specific focus and application. Computational Fluid Dynamics (CFD) models simulate coolant flow and heat transfer within the reactor core. These models are crucial for understanding thermal-hydraulic behavior and ensuring that reactor temperatures remain within safe limits. Neutron Transport Modeling describes the movement and interaction of neutrons within the reactor core. These models are essential for reactor kinetics, criticality analysis, and fuel burnup calculations. Thermal-Hydraulic Modeling focuses on the behavior of coolant and heat transfer in LWRs. These models predict temperature distributions, pressure changes, and help identify potential hotspots in the reactor core. System-Level Modeling considers the overall behavior of the entire reactor system, including primary and secondary loops, steam generators, and turbines. These models are used for reactor control and stability analysis. While modeling offers numerous advantages, it also comes with certain limitations. Models are simplifications of complex physical systems and may have inherent uncertainties. High-fidelity models can require significant computational resources, limiting accessibility.

For the purpose of power system analysis and electromagnetic transient (EMT) studies, it is a common practice to build a system-level differential equations model to describe the dynamic responses of nuclear reactors. Take PWRs as illustrations, in [13], [14], and [15], a 55th-order differential equations mathematical model of PWR and its simplified model are discussed in detail, and can be summarized as follows:

- *Point-reactor Neutron-kinetics Model* [16], [17], [18], [19], [20]: The underlying assumption is that the properties of the neutron density at each point of the nuclear reactor core vary with time independent of spatial location, and considering the reactor core as a point, a 2nd-order reactor prompt/delayed neutronic model can be obtained. This model performs well in cases where the local disturbance is not significant, or the reactor is close to criticality. In addition, for different critical states of the reactor, there are constant delayed neutron source approximation and prompt jump approximation, which can make one of the two variables of ordinary differential equations (ODEs) ignored. However, when the reactor deviates from the critical state, this model is no longer applicable. Generally, considering a reactor core with six groups of delayed neutrons.
- *Reactor Thermal-hydraulics* [21], [22], [23], [24], [25]: To represent the thermodynamics of the reactor core, Mann's model is widely used, which utilizes two well-stirred coolant lumps for each fuel node to describe the process of heat generation and transfer. This model is also called the nodal model, where one fuel and two coolant nodes ($1F/2C$) will derive a 3rd-order ODEs. Some scholars have also proposed multi-node models, i.e., a new heat balance model with $i_{th}F/2 * i_{th}C$. However, accordingly, the order of the equations will increase, which brings burdens to the solver. The paths where the coolant flows in and out are called the hot leg riser and downcomer, which are also referred to as hot leg and cold leg in some other literatures. These two components are usually treated as first-order lags, which introduces an additional set of 2nd-order ODEs.
- *Steam Generator* [21], [26], [27], [28], [29], [30]: The U-tube steam generators (UTSGs) and the helical coil steam generators (HCSGs) are commonly used as steam generators (SGs) among SMRs. Detailed modeling of SGs involves partial differential equations (PDEs) for mass and energy conversion, tube metal equations, primary and secondary loop energy balance equations, etc. The final state space form can be derived as 12 differential equations. Another simplified model, called the three-lump SG Model, contains only three segments: primary coolant, tube metal, and secondary coolant, which reduces the mathematical model of SG to a set of 3rd-order ODEs.
- *Turbine-Governor* [31], [32]: The choice of the steam turbine-governor model is relatively flexible, and the control strategy of the governor varies depending on whether the SMR is operated in grid-connected or islanded operation.

In addition, there are many other subsystems such as the plenum model, pressuriser model, condenser system, and circulating water system, etc., which are omitted here because they do not have a significant impact on the neutron density simulation results under ideal conditions.

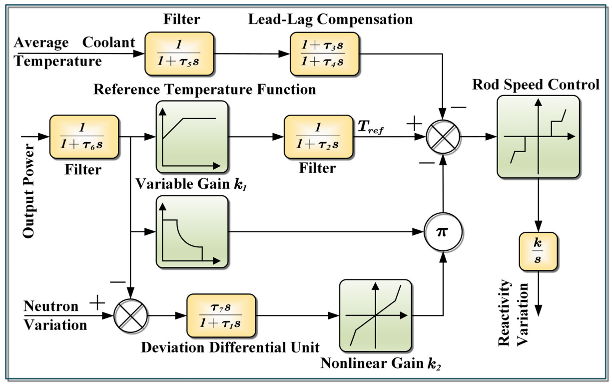

FIGURE 2. Coolant average temperature control system [12].

C. CONTROL STRATEGY

Control strategy is a pivotal element in the operation of LWRs. It plays a fundamental role in maintaining reactor stability, regulating power output, and ensuring safety. Without effective control strategies, LWRs could face instability and safety risks, making control systems an indispensable aspect of reactor operation. Control systems in LWRs manage a range of crucial functions, including power regulation, reactivity control, and safety mechanisms. These systems are responsible for adjusting control rod positions, controlling coolant flow rates, and responding to various operational conditions and disturbances. By doing so, they ensure that the reactor operates within safe power limits, maintains desired reactivity levels, and can respond to changes in electricity demand effectively.

In the context of nuclear reactions, reactivity refers to variations in the reaction rate or efficiency, typically stemming from changes in material or environmental parameters [33]. Reactivity is closely linked to the rate of nuclear reactions and the stability of the reactor. Changes in power can induce fluctuations in fuel or core temperature, leading to alterations in reactivity, which in turn impact the power output. These feedback effects hold significant implications for the safety of nuclear reactors. For instance, if an increase in power and temperature results in an increase in reactivity, it can lead to further escalation in both power and temperature. Without proper control, this unstable condition may result in accidents; this is referred to as a positive reactivity feedback effect. However, if an increase in power and temperature results in a reduction in reactivity, the initial power level will decrease as the temperature rises, thus maintaining core stability; this is known as a negative reactivity feedback effect. Clearly, the latter condition should inform the design of specific LWRs cores.

How to control excess reactivity? Besides relying on soluble boron in the coolant, another essential method is through the manipulation of control rods. Control rods are rod-shaped elements made of cadmium (Cd), boron (^{10}B), dysprosium (Dy) and other materials with strong neutron absorption capability, which can change the reactivity of the reactor core by absorbing neutrons [18]. For instance, in the designs of mPower and SMR-160, each assembly incorporates a control rod. In large PWRs employing boron for excess reactivity control, control rods are typically fully withdrawn. However, in some iPWRs, these control rods and their manipulation sequences permit the adjustment of excess reactivity reduction. In essence, the control system achieves the control of reactivity by manipulating the relative positions of control rods with respect to the fuel.

Control strategies in LWRs encompass a variety of approaches, each tailored to specific operational requirements: Feedback Control systems continuously monitor reactor parameters such as neutron flux, temperature, and pressure. They make real-time adjustments to control rod positions and coolant flow rates based on deviations from desired setpoints. For example, the steady-state operation schemes of PWRs include the constant steam pressure scheme, constant average coolant temperature scheme, constant coolant outlet temperature scheme, etc [12]. As shown in Figure 2, this is a three-channel PWR coolant average temperature control system, where $t_{1\sim7}$, k_1, k_2, and k are time constants and coefficients. The first channel is the coolant temperature measurement channel, with a leading and lagging unit used to compensate for the corresponding lag caused by the thermal inertia of the measurement channel. The second channel is the reference temperature setpoint channel, which generates the coolant temperature setpoint T_{ref} through inputting the set operating power and then passing it through a temperature customization function generator and a phase-lag element. The filter's role is to eliminate small and abrupt disturbance signals, preventing frequent movement of control rods. The last channel is the power mismatch channel, which generates a control signal to manipulate the control rods when there is a dynamic power mismatch but no significant change in coolant temperature. Combining the signals from these three channels, the control rod movement speed and direction are determined by the rod velocity control unit, thereby achieving the control objective.

D. SIMULATION

Simulation plays a crucial role in the field of nuclear engineering, enabling the analysis and understanding of complex reactor behavior. The current simulation software can be summarized as follows:

- *MCNP (Monte Carlo N-Particle)* [34]: MCNP is a Monte Carlo radiation transport simulation code widely employed for modeling nuclear reactions and radiation transport. It offers versatility in simulating various reactor types, including LWRs.
- *RELAP5-3D* [35]: RELAP5-3D is a computational tool tailored for dynamic analysis of nuclear reactors. It is capable of simulating transient behaviors in different reactor types, including PWRs and BWRs.
- *SCALE (Standardized Computer Analysis for Licensing Evaluation)* [36]: SCALE is a multifunctional tool for nuclear reactor physics and radiation shielding analysis. It is adaptable to various reactor types, including LWRs.
- *THERMIX* [36]: THERMIX focuses on simulating the behavior of fuel elements in BWRs. It considers aspects such as temperature, thermal expansion, and related phenomena.
- *RELAP-7* [37]: RELAP-7 represents an evolution of RELAP5, designed for simulating transient behaviors in nuclear reactors, including PWRs and other reactor types.
- *CASMO (Code for Advanced Spent Fuel Management)* [38]: CASMO is employed for analyzing the behavior of fuel assemblies across different reactor types, including LWRs.

TABLE 1. Examples of current LWRs (>10 MWe) proposed by commercial industries [5].

Reactor design	Power rating (MWe)	Country	Vendor/AE
Light water-cooled PWR			
ACP100	100	China	CNNC/Guodian
CAREM	27	Argentina	CNEA/INVAP
KLT-40S	35	Russia	OKBM
NuScale	60	United States	NuScale Power/Fluor
RITM-200	50	Russia	OKBM
SMART	100	S. Korea	KAERI
SMR-160	160	United States	Holtec
Light water-cooled BWR			
BWRX-300	300	United States/Japan	GE-Hitachi
VK-300	250	Russia	NIKIET

The future of LWR simulation software holds immense potential. Ongoing research and development efforts are likely to yield more sophisticated and integrated tools. These tools will incorporate improved physics models, advanced computational techniques, and enhanced data accuracy. These advancements will play a pivotal role in reactor design, safety assessment, and operational optimization.

E. REACTOR APPLICATIONS

LWRs exhibit versatility in addressing a wide array of energy and industrial needs. These diverse applications demonstrate the significance of LWRs in providing clean, reliable, and sustainable energy solutions for the present and future.

Electricity Generation [17]: LWRs primarily serve as reliable sources of electric power. They produce electricity by harnessing the heat generated from nuclear fission reactions. This application accounts for a significant portion of global electricity production, providing a stable and low-carbon energy source.

Sustainability [39]: LWRs play a role in reducing greenhouse gas emissions, contributing to global efforts to combat climate change. Their low-carbon footprint makes them a viable option for clean energy production.

F. POWER SYSTEM IMPACT

LWRs are a cornerstone of modern electricity generation, playing a pivotal role in the global energy landscape. These nuclear reactors, characterized by their use of ordinary water as both coolant and neutron moderator, have a profound impact on the stability, reliability, and sustainability of the electrical grid. Table 1 summarizes the distribution of commercial LWRs in the current global landscape.

One of the key advantages of LWRs is their ability to provide a consistent and reliable source of baseload power. Unlike some renewable energy sources, such as wind and solar, which are intermittent and weather-dependent, LWRs can operate continuously, providing a steady supply of electricity to meet the demands of the grid. This baseload power helps maintain grid stability by ensuring a constant supply of electricity even during peak demand periods. Furthermore, LWRs are known for their low greenhouse gas emissions. They produce electricity without the direct release of carbon dioxide, making them a crucial component in efforts to reduce greenhouse gas emissions and combat climate change. As countries seek to transition to cleaner energy sources, LWRs offer a valuable option for reducing reliance on fossil fuels. LWRs also contribute to grid resilience. Their ability to provide a consistent power supply is particularly important during emergencies, such as natural disasters or grid disturbances. In these situations, LWRs can help maintain critical infrastructure, provide essential services, and support the grid's quick recovery. However, it is essential to acknowledge the challenges associated with LWRs. Safety concerns, nuclear waste management, and the cost of construction and decommissioning are among the issues that require careful consideration. Additionally, the public's perception of nuclear power and regulatory hurdles can impact the expansion of LWRs in some regions.

In summary, LWRs have a significant impact on the electrical grid. They provide stable baseload power, reduce greenhouse gas emissions, enhance grid resilience, and play a crucial role in the transition to cleaner energy sources. While challenges exist, the contributions of LWRs to the electrical grid are undeniable, making them a critical component of the modern energy landscape.

III. LIQUID METAL-COOLED REACTOR

A. DESIGN

LMRs are a type of nuclear reactor design that uses a liquid metal as the coolant and heat transfer medium, such as sodium, lead, and lead-bismuth eutectic (LBE). It is constructed to withstand the extreme pressures and temperatures produced by nuclear reactions, as well as the liquid metal coolant that transfers heat from the reactor core to a steam generator that is connected to a turbine to produce electricity [40]. An LMR is composed of four essential parts:

The reactor core serves as the site for nuclear reactions, where solid fuel elements containing uranium oxide or plutonium oxide pellets are typically employed. These fuel elements are organized in a systematic arrangement and submerged within a liquid metal coolant, which circulates around the fuel. The primary objective of the core's design is to optimize the transfer of heat while maximising the concentration of fissile material in the core to maximise flux and minimise neutron loss [41].

TABLE 2. Liquid metal coolants characteristics [40].

Liquid metal coolant	Sodium	Lead	LBE	NaK
Melting point (K)	207.9	621.43	254.3	12
Boiling point (K)	1621	3180	3038	1445
Head transfer property	Excellent	Good	Good	Good
Thermal conductivity	High	High	Moderately High	Moderate
Reaction to water and air	Explosive	Low	Low	Moderate
Corrosion	No	Yes	Yes	No

The coolant system plays a crucial role in the circulation of liquid metal coolant within the reactor, facilitating the removal of heat produced by nuclear reactions. This system consists of two distinct coolant sub-systems: the primary and secondary coolant systems. Connecting these sub-systems is an intermediate heat exchanger (IHX) which transfers heat from the primary system to the secondary system. Additionally, coolant pumps are employed to ensure continuous circulation of the coolants throughout the LMR.

The steam generator comprises liquid water that absorbs heat from a secondary coolant and transforms it into steam. This steam is usually at high pressure and temperature, which is used as the driving force for turbine blades and converting thermal energy into mechanical energy [40]. The turbine is linked to a generator that generates electricity.

Control rods are employed to regulate the rate of nuclear reactions within the core. When inserted into the core, these rods impede the neutrons from instigating further fission, thereby decelerating or halting the nuclear reaction through neutron absorption. Conversely, by retracting the rods from the core, the nuclear reaction initiates and accelerates [42].

It is worth noting that various designs exist for similar types of LMRs, and each design may possess specific characteristics and variations tailored to its intended application and requirements. The designs of LMRs can be categorized into two main types based on how the coolant flow is arranged: pool-type and loop-type. In a pool-type LMR, the liquid metal coolant is contained within a large pool that surrounds the reactor core. On the other hand, in a loop-type LMR, the liquid metal coolant circulates through a closed loop system comprising the reactor core, IHX, and pumps. The provided illustrations in Figures 3 and 4 depict both the pool-type and loop-type LMR designs.

B. MODELING

The mathematical modeling of an LMR involves the development of mathematical equations and computational techniques to describe its behavior and performance. This includes various aspects, such as heat transfer, which takes

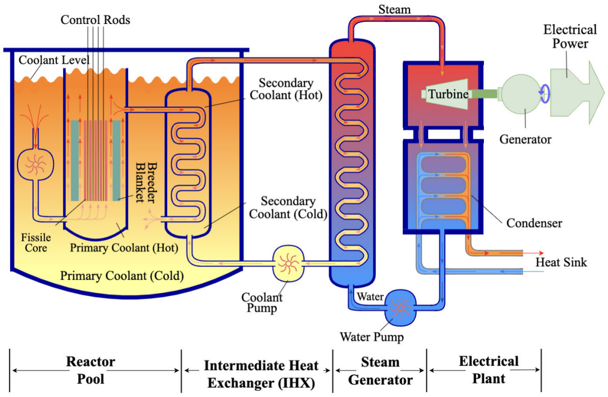

FIGURE 3. Liquid metal cooled breeder reactor - pool design.

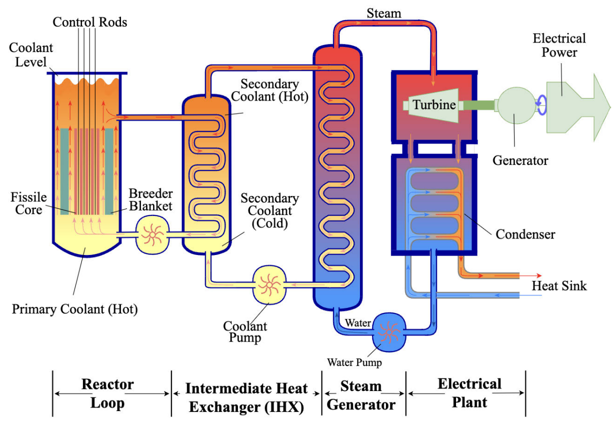

FIGURE 4. Liquid metal cooled breeder reactor - loop design.

into account elements like conduction, convection, and radiation heat transfer to simulate the exchange of heat among the fuel, coolant, and other reactor parts. Fluid dynamics relates to the behavior of the liquid metal coolant, including fluid flow, pressure drop, and velocity distribution inside the reactor core. Neutronics deals with the behavior of neutrons, including diffusion, absorption, and fission reactions, as well as the production and depletion of isotopes. Reactor kinetics focuses on the time-dependent behavior of the LMR core, incorporating equations that govern the rate of change of neutron population and power level, considering factors such as reactivity feedback effects and control rod movement. Material behavior considers properties such as thermal conductivity, temperature-dependent material characteristics, and interactions between different materials within the LMR. The subsequent paragraphs provide an overview of some crucial modeling aspects of LMRs. The heat convection model is the most important in an LMR as it facilitates the transfer of heat from the fuel to the coolant, which can be sodium, lead, or LBE. This model describes how heat is transported through the coolant via convection. In 2021, a one-dimensional, steady-state, axial convection model was developed to determine the coolant temperature and density [43]. This model focuses on the upward flow of liquid metal coolant through a single hexagonal assembly situated within the reactor core. To obtain the average enthalpy of each element, a first-order approximation is employed. Using this calculated enthalpy, along with the pressure and state equations for the specific coolant, the temperature and density of the coolant are computed for each node. These nodes are then utilized in subsequent finite element methods (FEMs) [44]. During the simulation of an LMR, the heat convection model is typically interconnected with various other multiphysics phenomena [45] such as neutron transport, thermal expansion, and potentially even electromagnetic effects. This coupling enables a comprehensive understanding of the system's behavior and accurate prediction of the temperature distribution, coolant flow patterns, and overall thermal performance of the reactor.

The heat conduction model in an LMR describes the transfer of heat in solid structures, including fuel assemblies, the reactor core, and surrounding materials. This process is responsible for distributing and dissipating heat generated within the reactor core. In the LUPINE multiphysics simulation suite, a one-dimensional, steady-state, radial heat conduction model is developed [43]. This model calculates the average temperatures of materials in hexagonal assemblies and at different axial levels, based on the corresponding liquid metal coolant temperature obtained from the axial convection model. In this radial conduction model, the thermal conductivities of the coolant bond and clad materials are assumed to be constant since their variations are minimal. By solving the heat conduction equation with appropriate boundary conditions and considering heat generation, the heat conduction model allows for the prediction of temperature profiles, hotspots, and overall thermal behavior within the solid components of an LMR [46].

The thermal hydraulics model is used to describe the behavior of the coolant, typically a liquid metal like sodium, lead, or LBE. This model includes aspects such as coolant fluid movement, heat transfer, and related phenomena. It holds significant importance in comprehending and forecasting the coolant's behavior and its influence on the reactor's overall performance [47]. By examining the coolant's behavior, temperature distribution, flow patterns, pressure changes, and overall thermal efficiency of the LMRs, the thermal-hydraulics model plays a crucial role in optimizing reactor design, evaluating safety margins, and ensuring efficient extraction of heat from the core [48].

The thermal expansion model explains how temperature changes can lead to alterations in the size and shape of structural elements. This phenomenon is crucial to consider when designing and operating LMRs because it directly impacts the core's integrity, performance, and the surrounding structures [49]. Additionally, thermal expansion plays a significant role in providing reactivity feedback. During the experiments conducted at EBR-II, operators intentionally subjected the reactor to Unprotected

Loss-Of-Flow (ULOF) and Unprotected Loss-Of-Heat-Sink (ULOHS) events [43]. Remarkably, EBR-II shut down safely without any intervention from the operators, solely relying on multiphysics feedback effects. This approach allows for the anticipation of dimensional changes and the resulting stresses in reactor components, utilizing information such as the coefficient of thermal expansion, material properties, and geometric limitations.

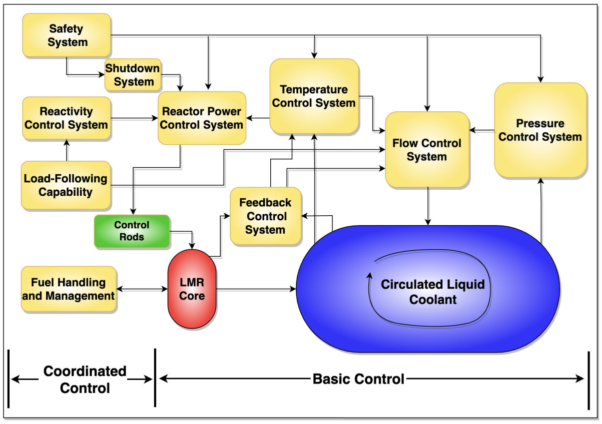

FIGURE 5. Liquid metal cooled reactor control structure [40], [55].

C. CONTROL STRATEGY

A specific method or technique is necessary to regulate and maintain the secure and efficient operation of a LMR. A suitable control strategy guarantees that the reactor operates within desired parameters, such as power level, temperature, and reactivity while maintaining safety margins. Figure 5 illustrates a typical control diagram with subsystems for the LMR. Several key aspects of a typical LMR control strategy are as follows:

- *Core Reactivity Control*: It is used to control the reactor core reactivity by inserting or withdrawing the control rods to maintain the reactor stability and achieve a desired power output [50].
- *Coolant Flow Control*: It is designed to monitor and regulate the flow rate of the liquid metal coolant to maintain optimal operation temperatures and prevent localized hotpots [51].
- *Temperature Control*: This control system involves adjusting the flow rate and temperature of the secondary coolant to regulate the reactor's primary coolant temperature [52].
- *Shutdown System*: It enables the rapid shutdown of the reactor in the event of abnormal conditions or emergencies [53].
- *Feedback Control*: This feedback control system is utilized to measure and adjust various parameters derived from the reactor feedback loops to maintain reactor stability and safe operations [54].

The choice of control strategies may vary depending on the design and configuration of the LMR. The following paragraphs outline some commonly employed controllers for LMRs.

The feedback controller constantly monitors various parameters within the reactor's feedback loops, including coolant temperature, reactor core power level, and neutron flux. It then modifies these parameters to maintain the desired operating conditions. By comparing measured values to a setpoint and utilizing the resulting error, the feedback controller determines necessary corrective actions. Through this feedback loop, the reactor's behavior is ensured to align with the desired performance.

The proportional-integral-derivative (PID) controller is a widely used method in control systems, valued for its ease of tuning and implementation. It functions as a feedback control algorithm with the objective of regulating a process variable to a desired setpoint by continuously adjusting various parameters [56]. The PID controller contains three subsystems [57]: the proportional control system that adjusts the control variables based on the reactor current error that represents the difference between the desired setpoint and actual value. The integral control system eliminates steady-state error by considering the cumulative sum of the LMR's past errors. The derivative control system predicts the future trend of the LMR error by considering the change rate of the reactor parameters, it aids in anticipating and responding to changes in the system. The PID controller can be mathematically represented by the following equation [58]:

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt}, \tag{1}$$

where $u(t)$ is the PID control output at time t, $e(t)$ is the error at time t, which is typically the difference between the desired setpoint and the process variable. The control signal is the sum of the error of proportional control system, integral control system, and derivative control system. K_p, K_i, and K_d are the proportional, integral, and derivative gains, respectively.

The Model Predictive Control (MPC) strategy is used for the thermal power control in the nuclear reactor core. The fundamental concept behind MPC is to employ a dynamic model of the reactor to predict its actions and enhance control measures within a specified time domain [59]. By continuously updating predictions and optimizing control inputs at each time step, this strategy adjusts the reactor's operating conditions to attain the desired performance [60].

The fuzzy logic control strategy is used to handle imprecise and uncertain parameters in the LMR. This strategy aims to enhance the reactor's performance by dynamically adjusting multiple parameters based on linguistic variables, fuzzy rules, and fuzzy inference [61]. Through the establishment of membership functions and rule sets, this approach effectively deals with complex and nonlinear relationships between the reactor's inputs and outputs.

The neural network control strategy uses artificial intelligent (AI) neural networks to model the complex behavior of the reactor and then make control decisions based on the model. By learning from past data, the neural network model adjusts the reactor parameters to achieve the desired behavior [62]. Additionally, through training on datasets containing reactor input-output combinations, the neural network model gains the ability to predict optimal control inputs based on the present LMR state.

D. SIMULATION

Simulation plays a crucial role in the design, analysis, and safety evaluation of LMRs. Simulations are instrumental in helping engineers and researchers comprehend the behavior of coolant, fuel, and reactor components under various operating conditions and accident scenarios. To achieve this, simulators employ advanced computational models and algorithms that forecast the thermal-hydraulic, neutronic, and fuel behaviour of a reactor system. The thermal-hydraulic simulation code primarily focuses on modeling heat transfer and the flow behavior of LMRs. This code utilizes CFD techniques to solve the governing equations, providing insights into the thermal-hydraulic aspects [63]. On the other hand, neutrons simulation codes employ mathematical models to calculate various parameters within the reactor, including neutron flux distribution and core power profiles [64]. These codes enable a comprehensive understanding of the neutronic behavior of the reactor system. Additionally, fuel behavior codes are utilized to simulate the response of nuclear fuel to operational and accident conditions. These codes incorporate different phenomena, such as fuel thermal expansion, cladding, and fuel melting, to accurately model the behavior of the fuel under various circumstances [65]. Different simulators of LMRs and their distinctive features are reviewed below.

SIMMER-III is a software designed specifically to analyze core disruptive accidents (CDAs) in SFRs [66]. It is a sophisticated computer program that employs multiple dimensions to replicate the complex dynamics of liquid metal coolant in various accident scenarios, including fuel pin failure, coolant boiling, sodium expansion, and core disruption [67].

TRACE is a comprehensive thermal-hydraulic system software that includes the capability to simulate LMRs. It integrates the most advantageous aspects of both the RELAP5 and TRAC codes to replicate the behavior of coolant flow, heat transfer, and system dynamics [68]. By incorporating diverse physical models and correlations, TRACE facilitates the analysis of steady-state and transient thermal-hydraulic conditions in LMR [69].

MELCOR is a fully integrated simulator designed to analyze the safety of LMRs. Its main objective is to replicate severe accidents, such as core meltdowns. MELCOR can simulate the progression of accidents, the transfer of heat, the release of fission products, and the interaction with coolant and structures. This simulation tool has gained extensive utilization in determining safety margins, assessing accident management strategies, and enhancing the overall safety of LMRs [70].

Code Saturne is a software application utilized in the analysis of thermal-hydraulics in LMRs. It functions as a CFD simulator [71], enabling the prediction of fluid flow, heat transfer, and other associated phenomena. With its ability to handle intricate geometries and simulate both steady-state and transient conditions of the LMR system, Code Saturne is extensively employed to optimize the thermal hydraulic performance of LMRs [72].

E. REACTOR APPLICATIONS

Worldwide investment has already been made in the development and demonstration of the unique liquid metal-cooled fast reactor technology exceeding US$ 50 billion. Research on LMR during the last decades has significantly improved our understanding of LMR safety, and it is predicted that LMR can achieve a very high degree of safety [40]. Nowadays, the SFR is the most commonly designed LMR. Many liquid metal-cooled SMRs have been designed and placed in China, France, India, Japan, the Russian Federation, and the USA. In Canada, some LMR programs are currently under development, one of them is the ARC-100 project in New Brunswick, which is an SFR. When the ARC-100 is completed, it will offer 100MW of electricity per year which will be enough to support 250,000 people in New Brunswick [73]. The BN-reactor, a type of SFR, has been constructed and operated by Russia since 1973. Presently, the operating BN-reactors include the BN-600 and the BN-800, with the latter being the world's largest operating fast reactor. Plans are underway for the BN-1200, to break the record held by BN-800 as the next generator fast reactor [74].

The LMRs have been considered as a potential technology for space power applications, specifically for long-duration space missions. The liquid metal coolant that the LMR transfers heat from the reactor core to a power conversion system, such as a Closed Brayton Cycle (CBC), to produce electricity [75]. Some conceptual designs and studies have been conducted by different organizations. The Kilopower program was successfully demonstrated by NASA in 2018, which explored the use of a small LMR concept called the "Kilopower Reactor Using Stirling Technology (KRUSTY)" that is a 1KWe liquid sodium cooled reactor [76]. SP-100 project was initiated by NASA in the 1980s to develop a compact nuclear power system for space applications, and one of the concepts was a either lithium or lithium-lead eutectic cooled reactor [77]. The Fission Surface Power (FSP) project is pronounced by NASA to develop a fission power system for long-duration lunar missions, and many different reactor concepts have been explored, including LMRs using liquid sodium or a sodium-potassium alloy as coolant [78]. TOPAZ and TOPAZ-II are a series of space nuclear systems that was developed by the Soviet Union, they are either lithium or lithium-lead alloy cooled reactors and the TOPAZ-II was successfully tested in the 1980s [79].

Russia has developed some submarines and icebreakers with Liquid Metal Cooled (LMC) technology [80]. Alfa-class submarines were one of the first Russian submarine developed by the Soviet Union in the 1960s, they used lead-bismuth eutectic as the coolant and were known for their high speed and was designed for anti-submarine warfare tasks. Akula-class Submarines were designed in the 1980s that were pressurized water reactors but incorporated with a liquid metal-cooled reactor for auxiliary purposes. This auxiliary LMR uses lead-bismuth as a coolant that provides power for non-propulsion systems, such as electricity generation and onboard services. The Lenin was the first nuclear-powered icebreaker in the world developed in 1957; it utilized a lead-bismuth cooled reactor that allows it to generate high power output and operate continuously in Arctic conditions, breaking through thick ice to open up shipping routes. Arktika-class icebreakers are a series of nuclear-powered icebreakers that were built by the Soviet Union, they were LMRs with liquid sodium as the coolant that provides high heat transfer properties and enables the icebreakers to efficiently generate the required power for heavy ice breaking. LK-60 YaMV-class Icebreakers are the latest generation of Russian nuclear-power icebreakers that feature two RITM-200 reactors, which are two pressurized water reactors that incorporate with LMRs using liquid lead-bismuth coolant for auxiliary systems and electricity generation [81].

F. POWER SYSTEM IMPACT

The introduction of an LMR into a power system can result in numerous notable effects that will enhance the performance of the entire power grid. The subsequent paragraphs outline several crucial factors regarding the impact of LMRs on the power system.

LMRs offer a notable boost in power generation capability when compared to traditional reactor designs [40]. This is because LMRs possess enhanced thermal conductivity due to their metal coolants, resulting in faster heat dissipation. Moreover, their higher thermal efficiency and power density enable greater electricity generation per unit of fuel, making LMRs the ideal choice in scenarios where high power density is preferred, like submarines.

The power grid stability can be improved by using LMRs, as indicated by the Control section using various controllers. The LMR controller enables effective regulation of reactor output by quickly adjusting its input to meet power requirements, thus mitigating the impact of fluctuations in renewable energy sources and ensuring a steady electricity supply [50].

The power system of LMRs has the capability to integrate with various renewable energy sources. LMRs are typically designed with adaptability, allowing them to enhance renewable energy resources like solar and wind power. This is achieved by offering flexible and manageable power generation [82].

LMRs possess the capability to serve both heat and electricity purposes [83]. This is achievable due to the high-temperature heat produced by the core of LMRs, which can be effectively utilized for district heating and various industrial procedures that require heat. Consequently, LMRs can generate heat and electricity concurrently, thereby enhancing the overall efficiency of the power system.

LMR's significant impact extends to advanced nuclear reactors, contributing to improved safety features. With a comparably high boiling point, LMR obviates the necessity to pressurize the reactor to raise the boiling point, which prevents the safety and maintenance issues encountered by traditional fast reactors. The LMR also provides excellent resistance to radiation damage [84]. which is an important consideration for long-term operation and fuel cycle efficiency, the liquid metal coolant acts as a barrier that protects the structural materials from the intense neutron flux and reduces the accumulation of damage caused by radiation.

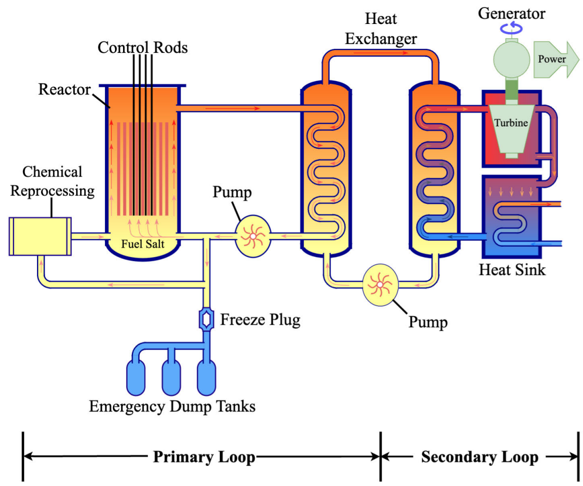

FIGURE 6. A conceptualized molten salt reactor.

IV. MOLTEN SALT REACTOR

A. DESIGN

MSRs are a revolutionary type of nuclear reactors that utilize liquid fuel in the form of molten salts. With several advantages such as high-efficiency electricity generation, enhanced safety features, high temperature process heat provision, and reduced nuclear waste production [85], MSRs have gained significant attention in the field of advanced nuclear energy.

The concept of MSRs was initially proposed by Oak Ridge National Laboratory (ORNL) in the 1950s. The first experimental liquid-fuel MSR, known as the Molten Salt Reactor Experiment (MSRE) [86], was constructed and operated by ORNL from 1965 to 1969. The MSRE was a 7.4MW(th) reactor that employed a mixture of lithium, beryllium, zirconium, and uranium fluorides (LiF-BeF2-ZrF4-Uf4) [87] as fuel salt. Additionally, MSRs can also incorporate thorium or plutonium isotopes [88], enabling breeding and thorium utilization capabilities. The choice of coolant can vary, with fluoride or chloride salts being common options [89], and FLiBe (Lif-BeF2) is a widely used coolant in MSRs.

The fuel salt, circulating through the core region, served as both the coolant and moderator in MSRs. This liquid fuel allows for excellent heat transfer properties and national convection, eliminating the need for high-pressure coolant systems. Graphite was used as the moderator material, surrounding the fuel salt channels to slow down neutrons and enhance the fission process.

As shown in Figure 6, in the past the MSR design typically consisted of two loops: the primary loop and the secondary loop. The primary loop circulates the fuel salt through the core region, utilizing pumps, heat exchangers, and piping to maintain proper flow and transfer heat to the secondary loop. The primary loop is designed for continuous operation and ensures efficient heat removal. The secondary loop is responsible for transferring heat from the primary loop to a power conversion system, such as a steam generator or a gas turbine system. It employs a separate molten salt coolant to extract heat from the primary loop and transfer it to the power conversion system. [90]. Current molten salt reactor designs use 3 loops where the first and the second loops are the same as previous designs. The 3rd loop is for the residual heat removal which ensures the stable operation of the reactor even during shutdown or emergency situations. This loop removes any excess heat from the reactor core, preventing overheating and maintaining the safety of the system. The Stable Salt Reactor (SSR) is a nuclear reactor design under development by Moltex Energy Canada Inc. has three loops.

MSRs can incorporate unique safety features, including a freeze valve system. In the event of emergencies, the freeze valve cools the fuel salt, causing it to solidify and halt the flow of the fuel through the core, providing inherent shutdown capability without relying on active systems [91].

Ongoing research in MSR design aims to build upon the lessons learned from the MSRE and explore advancements and modifications. This includes investigating alternative coolant options, such as chloride-based salts [89], to achieve higher operating temperatures and improved heat transfer properties. Researchers are also exploring different fuel salt compositions and additives to enhance fuel performance, reduce corrosion, and improve fuel cycle characteristics, including thorium-based fuel cycles [92]. Advancements in materials fuel processing, and safety systems are also being pursued to optimize fuel performance, enhance safety features, and incorporate advanced fuel processing techniques.

Building upon the MSRE, the concept of the Two-Fluid Molten Salt Breeder Reactor (MSBR) was also developed at ORNL in the 1970s. In the two-fluid design, the fuel and coolant are separated into two distinct loops. The fuel salt loop contains a higher concentration of fissile material, such as uranium-233 or plutonium-239, while the coolant salt loop acts as a neutron moderator and a medium for transferring heat to the power conversion system.

The MSBR concept, with its two-fluid design, is well-suited for exploring the thorium fuel cycle. The thorium fuel cycle is an alternative to the traditional uranium fuel cycle used in most nuclear reactors. In the thorium fuel cycle, by incorporating thorium as a fertile material in the fuel salt loop, thorium-232 is irradiated with neutrons, leading to the production of uranium-233, a fissile isotope. The uranium-233 can then be used as fuel in a nuclear reactor. The MSBR's breeding capability allows for the continuous production of fissile material while generating power.

The primary advantage of the two-fluid MSBR concept is its ability to breed more fissile material than it consumes, making it a potential breeder reactor. By selectively removing fission products and adding fertile material, such as thorium-232, to the fuel salt loop, the reactor can generate additional fissile material while producing power. This breeding capability has drawn interest due to the potential to sustain a long-term supply of nuclear fuel.

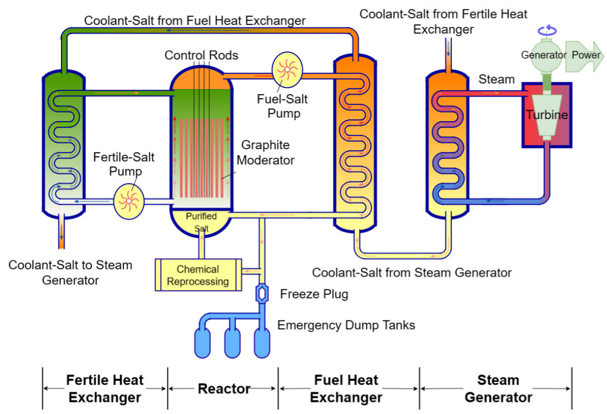

FIGURE 7. A conceptualized molten salt breeder reactor.

Through these research efforts, the aim is to overcome challenges and pave the way for the deployment of future MSR systems with improved efficiency, safety, and sustainability. MSRs hold significant potential as a viable and sustainable option for clean and efficient nuclear energy generation.

B. MODELING

To better understand the behavior and characteristics of the MSRs, various modeling technique modeling techniques have been employed. These models aim to provide insights into various aspects of the reactor system, including neutronics, thermal-hydraulics, and fuel salt chemistry.

Neutronics models play a crucial role in studying neutron behavior within the reactor, facilitating an understanding of neutron flux, reaction rates, and reactivity control. By accurately simulating neutron transport and interactions, neutronics models evaluate core behavior, fuel utilization, and safety margins. The model also accounts for delayed-neutron losses in the external loop, including those occurring through the heat exchanger [93]. The ultimate goal is to analyze reactor transients occurring during normal operation as well as plausible incident scenarios [85]. Thermal-hydraulic models focus on capturing the coolant behavior and heat transfer within the MSRs. They analyze fluid flow patterns, temperature distributions, and heat exchange processes to ensure efficient heat removal and optimize reactor performance. The most typical scheme in MSR involves a point kinetic model combined with lumped thermal-hydraulic parameters [94], [95]. Additionally, the point kinetic model can be used alongside single-channel thermal-hydraulic models to analyze reactivity insertion accidents, inherent safety design, and reactivity-initiated transients [96], [97], [98]. In 2016, [99] utilized the RELAP5 code to solve the traditional point kinetic model with the multi-channel thermal-hydraulic model, resulting in a more efficient and suitable simulation analysis.

As the point dynamic model is developed, multi-dimensional neutronic dynamic models were proposed to improve the accuracy and efficiency of transient simulations. In 2003, [100] introduced a 1D dynamic model for calculating steady-state status and analyzing accidental transients. In 2006, [101] developed a 2D dynamic model utilizing discretized time-spatial dependent equations to study transient characteristics. Furthermore, in 2007, [102] proposed a 3D neutronics and thermal-hydraulics model, consisting of three 1D equations in the Cartesian geometry and solved by polynomial expansion. Similar efforts with the multi-channel model include MOREL code [103] and TMSR-3D [104].

Fuel salt chemistry models focus on the chemical behavior of the fuel salt, including fission product behavior, transmutation rates corrosion, and the impact of impurities. Understanding these chemical aspects is crucial for optimizing fuel processing techniques, analyzing fuel behavior, and ensuring the safe and efficient operation of the reactor. Computational models are employed to simulate chemical reactions and provide insights into fuel salt composition and behavior. In 2020, [105] developed a dynamic model to analyze the startup and shutdown behavior of xenon in MSR using a single parameter set.

Multi-physics modeling (MPM) integrates different physics phenomena to provide a comprehensive understanding of the MSR system. This approach studies transient behavior, optimizes core configurations, and assesses safety features by considering the interplay between thermal-hydraulics, neutronics, and fuel salt chemistry. Multi-physics models enhance the accuracy and realism of the overall system representation. In 2011, [106] proposed an MPM to analyze MSR behavior with the spatial effects of the most relevant physical quantities. In 2020, [107] developed a multi-physics model to predict the behavior of inert gas bubbles in MSR.

MSR models encompass thermal-hydraulic, neutronics, fuel salt chemistry, and MPM, and so does the MSBR model. These models contribute to a better understanding of MSR behavior and performance, facilitating optimization, safety analysis, and the development of future reactor designs. By simulating key aspects of the MSR system, experiment models play a vital role in advancing the field of MSR research and development.

C. CONTROL STRATEGY

Effective control strategies are essential for the safe and efficient operation of MSRs. These strategies consist of several key elements aimed at regulating the reactor's power, temperature, and composition. Figure 8 illustrates a control diagram with subsystems for the MSBR. One common approach is the use of control rods or other neutron-absorbing materials to modulate neutron flux and reactivity. These rods, usually made of neutron-absorbing materials like boron or hafnium, can be inserted or withdrawn from the core to control the neutron flux and maintain the desired power level. The control rods are moved by mechanical or hydraulic mechanisms based on signals from the reactor instrumentation [108]. By inserting or removing these absorbers, the neutron population and fission reactions can be controlled, enabling power regulation and maintaining reactor stability [109].

Temperature control plays a critical role in MSRs to ensure reactor integrity and maximize thermal efficiency. MSRs typically employ a primary coolant loop to circulate the molten salt fuel through the core and a secondary loop to transfer the heat to a power conversion system [110]. Control systems monitor temperature at various locations in the reactor and adjust parameters like coolant flow, power output, or control rod position to maintain temperature within acceptable ranges. Adjusting the flow rates in these loops ensures that the fuel and structural materials remain within their operational limits. Some designs incorporate additional mechanisms like passive safety systems, such as freeze plugs or drain tanks, to handle excessive heat and prevent fuel damage [111].

Maintaining the desired composition of the fuel salt is crucial for optimal reactor performance. MSRs often employ a continuous online fuel process system to remove impurities and replenish the fuel to compensate for fission product losses [87], [112], [113]. This strategy ensures that the fuel salt remains within the desired composition range, avoiding excessive accumulation of neutron poisons and impurities that could hinder reactor operation.

Incorporating advanced monitoring and instrumentation is a key control strategy of MSRs. Strategically placed sensors and detectors throughout the reactor measure critical parameters such as temperature, pressure, flow rate, and salt composition [114], [115]. These measurements provide real-time feedback to the control system, enabling prompt adjustments and responses to changing conditions.

The control strategy of MSRs encompasses the regulation of power, temperature, and reactivity. It involves using neutron absorbers for reactivity control, primary and secondary coolant loops for temperature management, continuous online fuel processing systems for composition control, and advanced monitoring and instrumentation for real-time feedback. These elements are crucial for ensuring the safe and efficient operation of MSRs and contribute to the development of advanced nuclear energy systems.

D. SIMULATION

Simulations of MSR are crucial for validating the design, exploring operating scenarios, and guiding the development of future MSR concepts. Accurately representing the behavior of liquid fuel is a major challenge in modeling MSRs. To overcome this challenge, researchers have devised various approaches.

One such method is Monte Carlo, which simulates the behavior of individual particles, such as neutrons, to calculate key reactor parameters such as the neutron flux, fuel burnup, and reactor kinetics. However, the high computation cost of the Monte Carlo limits its application in iterative loops or repeated calculations with varying input conditions [116]. Nevertheless, Monte Carlo is widely used in MSR simulations. In 2018, [117] employed the Monte Carlo code Serpent to analyze the first zero-power critical experiment at MSRE. Similarly, in 2020, [118] used the MCNP code to examine the core assembly and primary loop components inside the core vessel of MSRs.

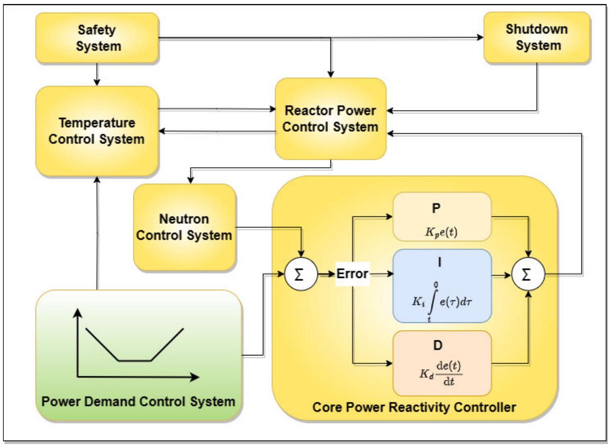

FIGURE 8. Molten salt breeder reactor control structure.

CFD is another useful tool for MSR simulation, as it can model the behavior of the fluid fuel and coolant. CFD is typically used in combination with Monte Carlo simulation to provide a more comprehensive understanding of reactor behavior. Some notable CFD codes used in MSR modeling include OpenFOAM [119] and ANSYS Fluent [120]. In 2013, [121] introduced the Monte Carlo code SERPENT-2 and multi-physics toolkit OpenFOAM to compute the effective delayed neutron fraction. Furthermore, in 2019, [122] developed 3D fluid flow and heat transfer models within a commercial CFD code to simulate the flow and heat transfer characteristics in MSRs. In the same year, [123] used the OpenFOAM CFD toolkit to investigate and effects of thermal striping on MSR fuel salt.

Several studies have employed alternative simulation approaches to investigate various aspects of MSR behavior and performance. For example, [124] and [125] utilized the GOTHIC code to benchmark steady-state and transient conditions of the fuel salt loop in MSRs. In 2009, [126] modified an in-house-developed 2D multigroup diffusion DALTON code to implement the time-dependent neutron physics models. Additionally, in 2022, [127] introduced a GPU-based whole core transport code ThorMOC to simulate a quasi-2D delayed neutron precursor (DNP) drift model of MSRs.

Many simulation tools are built based on the simulation methods above and for example, SaltProc, an online reprocessing simulation package that enhances the capabilities of the SERPENT2 continuous-energy Monte Carlo Burnup calculation code to simulate MSR online reprocessing by modeling the changing isotopic composition of MSR fuel salt [128], [129].

Simulating MSR serves as a valuable tool for understanding the behavior and performance of liquid-fueled MSRs. Ongoing advancements in simulation techniques, validation through experimental data, and model development contribute to the continuous improvement of MSR simulations, guiding the development of future MSR concepts and facilitating their safe and efficient deployment.

E. REACTOR APPLICATIONS

The history of MSR applications spans approximately 70 years. The first MSR, known as Aircraft Reactor Experiment (ARE), was constructed by ORNL in the 1650s [130], as a part of Aircraft Nuclear Propulsion (ANP) program [131]. It successfully operated a small thermal neutron flux MSR using a mixture of lithium and beryllium fluoride salts as the fuel, generating 96MWhr of energy. Following the ARE, the MSRE was a groundbreaking demonstration reactor operating from 1965 to 1969. The MSRE showcased the safe operation of a liquid-fueled reactor and highlighted the potential benefits of MSRs, including improved safety, fuel utilization, and waste management [86]. The MSBR was a conceptual design that built upon the successes of the MSRE [132]. It aimed to be a breeder reactor, capable of producing more fissile material than it consumed. However, the MSBR was cancelled in 1976 due to its limited political and technical support, as well as competition from the fast breeder program [133]. Subsequently, ORNL proposed the Denatured Molten Salt Reactor (DMSR) for high-level resource optimization and low fuel cycle costs [134]. In addition to the contribution of ORNL, the UK Atomic Energy Research Establishment (AERE) put forward a Molten Chloride Salt Fast Reactor with a capacity of 2500MWe in 1964 and 1965 [135]. Moreover, in 1990, a Japanese group developed Thorium Molten-Salt Nuclear Energy Synergetics (THORIMS-NES), a molten salt breeding fuel cycle system. Building upon this system, the International Thorium Molten-Salt Forum (ITMSF) developed MSR-FUJI, a modular reactor with an electrical capacity of 200MWe per module [136].

Since 2000, MSRs have gained significant interest as a promising candidate for Generation IV nuclear energy. France's National Centre for Scientific Research (CNRS) has focused on the development of a 1500MWe Molten Salt Fast Reactor (MSFR) since 2004, specifically designed without any solid moderator to avoid no graphite lifespan issues [137]. In 2011, the Chinese Academy of Sciences designed the Thorium Molten Salt Reactor (TMSR) nuclear energy system to optimize the utilization of thorium-based nuclear energy and enable hybrid nuclear energy applications [113], [138]. In Russia, the development of a Molten Salt Actinide Recycler and Transmuter (MOSART) took place, utilizing compositions of transuranic elements (TRU) trifluorides [139], [140]. As a part of the TMSR concept, a 168MWe liquid-fuel TMSR (TMSR-LF) was introduced as a technical route for the utilization of thorium fuel and fuel breeding. Notably, Moltex Energy Canada Inc. has developed the Stable Salt Reactor (SSR), while the Canadian company Dual Fluid Energy Inc. developed the Dual Fluid Reactor (DFR), utilizing molten actinide chloride salts or pure liquid actinide metal as the fuel [141]. Additionally, Terrestrial Energy, also a Canadian company, has proposed the Integral Molten Salt Reactor (IMSR) [142].

Other applications of MSRs include: the Molten Chloride Fast Reactor (MCFR) proposed by Terrapower LLC [143], the Fluoride Salt-cooled High-temperature Reactor (FHR) introduced by the Kairos Power company [144], the ThorCon MSR developed by US-based Thorcon company [145], the Heavy Water-moderated Molten Salt Reactor (HWMSR) developed by Copenhagen Atomics in Denmark [146], and the Transatomic Power (TAP) MSR introduced by the Transatomic Power Corporation in USA [147].

These numerous types of MSRs proposed worldwide illustrate the diverse approaches and ideas in the development of this advanced nuclear technology. They showcase ongoing efforts to explore and optimize the potential of MSRs for safe and sustainable energy generation.

F. POWER SYSTEM IMPACT

MSRs have the potential to revolutionize the field of nuclear energy due to their unique features and numerous advantages. The impact of MSR technology spans various aspects, including safety, fuel utilization, proliferation resistance, and waste management.

MSRs excel in safety with features like a negative temperature coefficient of reactivity, stable coolant, and low-pressure operation [148]. The liquid fuel in MSRs enables effective passive cooling and inherent safety. The negative temperature coefficient of reactivity ensures automatic slowing down of the core during overheating, preventing runaway reactions and meltdowns. MSRs also operate at atmospheric pressure, eliminating the risk of high-pressure explosions associated with traditional pressurized water reactors. These safety features make MSRs highly attractive for next-generation nuclear power plants.

In terms of fuel utilization, MSRs offer superior efficiency compared to conventional reactors. The continuous fuel flow allows for online chemical processing to remove fission products, extending fuel lifetimes and achieving higher burning rates [149], [150]. MSRs can utilize various fuel types, maximizing nuclear resource utilization. The high burning rate significantly reduces radioactive waste production compared to conventional reactors. Besides, MSBRs offer the advantage of using thorium as a fuel source. Thorium is more abundant than uranium, and its utilization in MSBRs can help reduce dependence on conventional uranium fuel. This diversification can enhance the overall resilience and security of the power system by reducing reliance on a single fuel source.

MSRs possess notable non-proliferation features, preventing the illicit acquisition of nuclear weapons and materials by sovereign countries [151]. Continuous fuel processing eliminates the need for fuel fabrication plants, minimizing the risk of diversion of fissile materials for weapons purposes. Some MSR designs using thorium fuel hinder the production of weapons-grade plutonium. These attributes enhance nuclear non-proliferation efforts and contribute to global security.

Waste management is another area where MSRs have a profound impact. Online removal of fission products and continuous fuel processing enables the extraction of valuable isotopes like Molybdenum-99 for medical and industrial applications [152]. The reduced volume and longevity of waste produced by MSRs contribute to the overall sustainability and environmental impact of nuclear energy.

MSRs have a transformative impact on nuclear energy. Their widespread deployment has the potential to revolutionize the energy landscape, providing a safe, sustainable, and environmentally friendly solution to meet the growing energy needs of the future. Further research and development in MSR technology are vital to unlock its full potential and realize its significant impact on the global energy sector.

V. GAS-COOLED REACTOR

A. DESIGN

Reactor technology using gas as coolant is broadly divided into four stages, early GCRs, improved GCRs, HTGRs, and moduler high-temperature gas-cooled reactors (mHTGRs) [153]. Both Magnox (the early GCR) and AGR (the improved GCR) reactors use carbon dioxide as a coolant. Magnox reactors are limited by uranium metal and magnesium alloy envelopes that cannot withstand higher temperatures, with carbon dioxide exit temperatures generally around 336°C, while AGR reactors use enriched uranium as fuel, increasing the power density and thermal efficiency of the reactor, with carbon dioxide exit temperatures as high as 648°C. HTGRs, including VHTRs as fourth-generation nuclear reactors, can provide high-temperature thermal energy from 750°C to 950°C using graphite as a moderator, low-enriched uranium or highly enriched uranium and thorium oxides (or carbides) as fuel, and inert gas helium as coolant. HTGRs use high-temperature resistant ceramic-type clad pellet fuel elements, such as TRISO pellets. Based on the above-mentioned clad pellet fuel technology and modularity, a mHTGR characterized by miniaturization and inherent safety has been formed. The reactor is safer and more economical as the maximum fuel temperature will not exceed the temperature limit of 1620°C in the event of an accident [154].

The components of an HTGR include the reactor, steam generator, turbine generator, steam coupled box system, main helium fan, feed pump, and reactor control rod system. A conceptualized HTGR is illustrated in Figure 9. The control rods are used to absorb neutrons and change the reactivity in the nuclear core to modify the heat power. The cooling system consists of two circulation loops. The primary loop is connected to the core, the SG, and the second loop. Coolant circulates in both loops and transfers heat. And then, the steam drives a turbine, which in turn drives a generator to produce power, completing the conversion of thermal and electrical energy. A cooling loop outside the turbine outlet condenses the steam from the turbine outlet back into water and pumps it back into the SG inlet. A heat exchanger and loop are used to extract thermal energy for external use [155].

HTGRs can be divided into two main types, spherical bed reactors, and prismatic reactors, according to the characteristics of the reactor core structure. The design concept of a small-capacity spherical-bed mHTGR with a thermal power of 200MW was first proposed in Germany in 1979, and a lot of research and development work has been carried out in Germany to build an HTGR (AVR) experimental reactor and a high-temperature thorium reaction (THTR) industrial demonstration reactor. Around 2000, China constructed their own test mHTGRs, i.e. the world's first 10MWt pebble-bed high temperature gas-cooled test reactor (HTR-10) and first industrial demonstration power plant for mHTGR (HTR-PM). As a subsequent commercial version of the HTR-PM, the HTR-600 [156] parallels six Nuclear steam supply system (NSSS) modules connected to turbines to form a 600MWe HTGR nuclear power plant. The 400MWt pebble-bed modular reactor (PBMR) developed in South Africa [157], unlike the HTR-10 power conversion system, uses a direct cycle gas turbine power generation type with a reactor outlet coolant temperature of 900°C. The United States and Japan have mainly developed prismatic reactors. The United States constructed the Peach Bottom experimental reactor and the Fort St. Vrain (FSV) industrial demonstration reactor. Japan constructed the 30MWt HTTR high-temperature experimental reactor, which is the first reactor in the world with a reactor exit coolant temperature of 950°C. The U.S.-designed Gas Turbine Modular Helium Reactor (GT-MHR) will be built as a single 285MWe module with a direct helium-driven turbine. There is also a smaller version of this reactor, the 10-25MWe Remote Site Modular Reactor (RS-MHR) proposed by General Atomics (USA). Based on the GT-MHR, Famatron developed the VHTR with a reference design of 600MWt and a target value of 1000°C for the core exit temperature, with a 2-loop system-hybrid indirect cycle, avoiding the possibility of contamination of the power generation system or the hydrogen production plant with radionuclides from the core.

B. MODELING

Modeling of HTGRs can be divided into three modeling approaches: physical modeling, thermal modeling, and dynamic mathematical modeling.

Physical modeling refers to the mathematical description and calculation of the neutron flux distribution, power distribution, reactivity, control rod effects, and fuel consumption of an HTGR. It takes into account the geometry of the core, the composition and arrangement of the fuel elements, the thickness and material of the reflective layer, and other factors. For example, [158] used MELCOR software to model the mHTGR of General Atomics, enabling a system-level analysis of the thermal hydraulics and severe accidents of the mHTGR. Reference [159] used RELAP5 to physically model the helium flow, the spherical bed core, and the reflector assembly of the Experimental Power Reactor (EPR) to achieve steady-state and transient analysis of the EPR. Reference [156] build the physical system of HTR-PM600 based on the fundamental conservation equations of fluid mass, energy, and momentum, and use differential equations to represent the kinetic behavior of HTR-PM600. Reference [160] presented a feasibility study of a quarter-scale physical model of the core of an HTGR.

Thermal modeling provides a mathematical description and calculation of the thermal-hydraulic properties of an HTGR, such as coolant flow and heat transfer. It considers the power of the core, the state of the coolant, the thermal conductivity of the fuel and the structure, and the equations of flow, heat transfer, and state. For example, [161] introduced a RELAP5-3D/PHISICS-based modeling method for HTGR cores based on neutron flux calculations and thermodynamic calculations, which can simulate different operating conditions of core behavior under hydrothermal feedback, such as steady-state, load-following and accident scenarios. Reference [162] composed the coolant flow path in detail and improved the original thermal analysis model of HTR-10 built under the THERMIX program. Reference [163] used the finite difference method (FDM) and response surface method (RSM) for thermal modeling to achieve multi-objective optimization of a spiral tube steam generator.

To study the dynamic characteristics of an HTGR nuclear power plant and, on this basis, to study the control methods and thus design the corresponding control system, a plant-wide dynamic mathematical model of the entire plant must be developed. The model takes into account, among other things, the variation of neutron and thermal parameters of the core, as well as external or control signals. Dynamic process modeling includes distributed parameter models and lumped parameter models. Distributed parameter models are usually described by partial differential equations, such as the THERMIX procedure in [162], but the complexity of this model is not suitable for the design of control systems. The lumped parameter model is usually described by ODEs, which are mainly used to describe a simplified minimum dynamics model and facilitate the design of control systems. For example, [164] described the dynamic

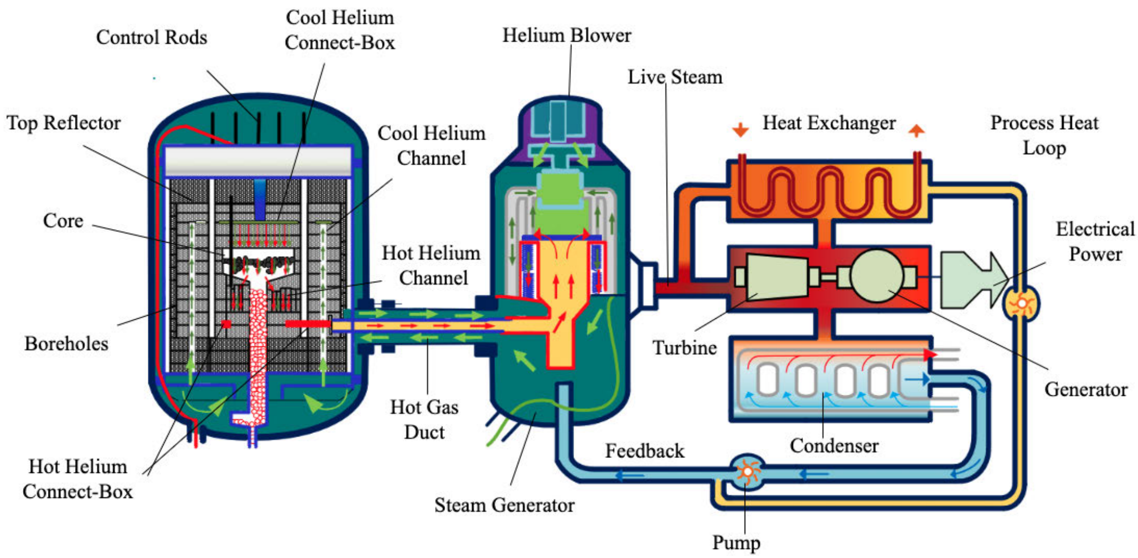

FIGURE 9. A conceptualized high-temperature gas-cooled reactor [155].

model of the lumped parameters of each modeling object of HTR-PM in a state-space manner to provide a basis for the subsequent analysis and synthesis of the control system [165], where [165] used the TS fuzzy technique to model the nonlinear dynamics of the HTGR system considering the uncertainty of the system. Reference [166] established a dynamic model of 5MW Mi-HTR (micro-high-temperature GCR) by theoretical derivation, including the reactor model and the energy conversion system model, and linearized and Laplace transformed the model to obtain the transfer function model between different inputs and outputs.

C. CONTROL STRATEGY

In the early stages of reactor control research, general control methods for HTGR nuclear power plants used decentralized control structures consisting of multiple single-input single-output (Multi-SISO) feedback control loops based on PID control algorithms, such as Peach Bottom, FSV, THTR-300, HTR-Module, HTR-10 [164] power plant control schemes. With the rapid development of digital computers, the modern control theory of linear power systems started to be applied to reactor control in the early 1990s. For example, [167] proposed the state feedback-assisted classical control method to improve the reactor power control performance. Reference [168] applied the LQR/LTR technique, which can improve the robustness of the closed-loop stability and thus further improve the temperature transients. Reference [169] conducted a study on the linear optimal control of the reactor core system based on the reactor neutron dynamics theory.

HTGRs are nonlinear and complex systems, such as model uncertainties, parameter variations with fuel burnup, and external environmental factors such as climate conditions, and grid demand. In HTGR-based power plants, power supply and demand must be balanced by generation or load, so the HTGR requires an automatic control system to track load variations and operate efficiently and stably at the desired power level. Currently, a wide range of control mechanisms have been developed by researchers in the related papers, from dynamic surfaces [170] to optimal and robust control [171], sliding mode control (SMC) [172], fuzzy control [173], deep reinforcement learning [174], neural networks [175], [176], improved PID control [177], dynamic matrix controllers (DMCs) [178], etc. Specifically, [172] designed a nonlinear tracking controller for mHTGR based on the SMC scheme and TS fuzzy technique to achieve the power level control objective under variable load conditions. Reference [175] established an multi-layer perceptron (MLP) compensated output-feedback power level controller for mHTGR to suppress the negative effects caused by system parameter uncertainty using the strong approximation capability of a multilayer perceptron artificial neural network, and verified by numerical simulation. For states that cannot be measured by the system, an observer is often used to recover the unmeasured states online [179]. Reference [177] used an improved PID controller to control the start-up, shutdown, and load-tracking control system of a VHTR. Reference [178] used the MPC method based on DMC for supervisory control of NSSS to regulate the NSSS thermal power by adjusting the neutron flux, coolant flow rate, and other set values. Some evolutionary computational algorithms, such as genetic algorithms (GA) [163], can be applied for parameter optimization of HTGR.

As shown in Fig. 10 the structure of the control system of the nuclear reactor, including the basic control, coordinated control, and the main control of three parts. Among them, the basic control includes the reactor, steam generator, and helium fan, which are mainly responsible for maintaining the thermal balance and helium cycle of the nuclear reactor; the coordinated control includes the feed water flow, output power control, and load handling command loop, which are mainly responsible for regulating the output power and feed water flow of the nuclear reactor according to the commands. The main control section includes the command, grid frequency, and operator, which are mainly responsible for receiving external commands and sending signals to the coordinated control section. The specific working principle is as follows: firstly, the main controller part regulates the output power control system and the load handling command loop according to the operator's instruction, to change the target values of the output power of the reactor and the feedwater flow rate; then, the basic control part and the coordinated control part regulates the rotational speed of the helium fan and the flow rate of the feedwater flow system according to the actual temperatures and pressures of the reactor and the steam generator, to make the reactor and steam generator to reach the target state; finally, the reactor control system adjusts the position of the control rods according to the signals from the output power control system, thus starting or stopping the chain reaction in the nuclear reactor.

D. SIMULATION

Numerical simulation is mainly based on physical equations of the HTGR system, establishing the corresponding partial differential equations or algebraic equations, and then using finite difference, finite element, finite volume, and other numerical methods to solve, to obtain the required simulation results. For example, [180] used the finite element method to analyze the temperature field of the HTR-10 ultra-high temperature operating core, considering the random distribution of fuel spheres and graphite spheres, helium flow, etc. Reference [181] constructed a three-dimensional coupled model using CFD software to simulate the flow and heat transfer processes within the core for helium cooling at rated operating conditions and compared the results with those of THERMIX software. Reference [182] carried out the flow heat transfer calculations of the space GCS core using the Monte Carlo method and Star-CCM+ software. Numerical simulation methods can provide detailed information on HTGRs, but they also face challenges such as large computational volumes.

The modularization-based system simulation method mainly divides the HTGR system into several modules according to its structure and functions, then describes the input-output relationship of each module using empirical formulas, simplified models, and state spaces, and finally realizes the simulation of the whole system by connecting each module. For example, [183] used self-developed simulation software based on the aggregate parameter method to achieve a fast and flexible simulation of the heat pipe cooling stack system and an effective treatment of multi-physics coupled processes. Reference [156] developed a dynamic model based on state space for simulating the processes of thermal hydraulics, neutron physics, and control strategy of the six-module HTGR system HTR-PM600, and used MATLAB/Simulink software and Simulink Coder software for offline simulation and real-time simulation.

The data-driven simulation method based on the experimental data or operational data of the HTR-PM system is mainly used to build the corresponding data models, and then machine learning or artificial intelligence and other techniques are used for data analysis and prediction to obtain the desired simulation results. For example, [184] used a deep learning model as a simulation method to rapidly predict the apparent factor in a nuclear HTGR (HTR-PM) to analyze the radiation heat transfer behavior in a pellet stack.

E. REACTOR APPLICATIONS

HTGR can be used to generate electricity in several different ways. The most common method is to use a helium-steam cycle to generate electricity in a loop. In this case, the helium coolant absorbs heat in the reactor and then flows through the steam generator, which transfers the heat to the water in the second loop, converting it to steam. The steam pushes the turbine to rotate and drives the generator to generate electricity. Another method is to generate electricity using a direct helium cycle (helium turbine). In this case, the helium coolant absorbs heat in the reactor and drives the turbine directly. The turbine drives the generator to generate electricity and also drives the compressor to compress the helium, which is compressed, heated, and then re-entered into the reactor to be heated repeatedly. In addition, HTGR can be used in combination with other types of energy conversion systems, such as the Brayton cycle [185], etc.

HTGR hydrogen production mainly uses the high-temperature heat it generates as the heat source to produce hydrogen through methane steam reforming, high-temperature electrolysis of water, and thermochemical cycle of water decomposition [186]. HTGR hydrogen production is characterized by low carbon emissions, high efficiency, and high reliability. Methane steam reforming hydrogen production is the reaction of natural gas with water vapor at high temperature to produce hydrogen, and the temperature range required for the reaction is 500°C-950°C; high-temperature electrolysis water production is the electrolysis of water vapor by using the heat source generated by HTGR at 800°C-1000°C, thus reducing the consumption of electricity. Thermochemical cyclic decomposition of water for hydrogen production is achieved by dividing the water pyrolysis process into several chemical reactions as raw materials, and the intermediate materials can be recycled. The temperature of each chemical reaction in the cycle is between 800°C-900°C.

HTGRs can be used to desalinate seawater using the high-temperature steam or low-temperature waste heat they generate to solve the problem of water supply in areas where freshwater resources are scarce [187]. There are three main

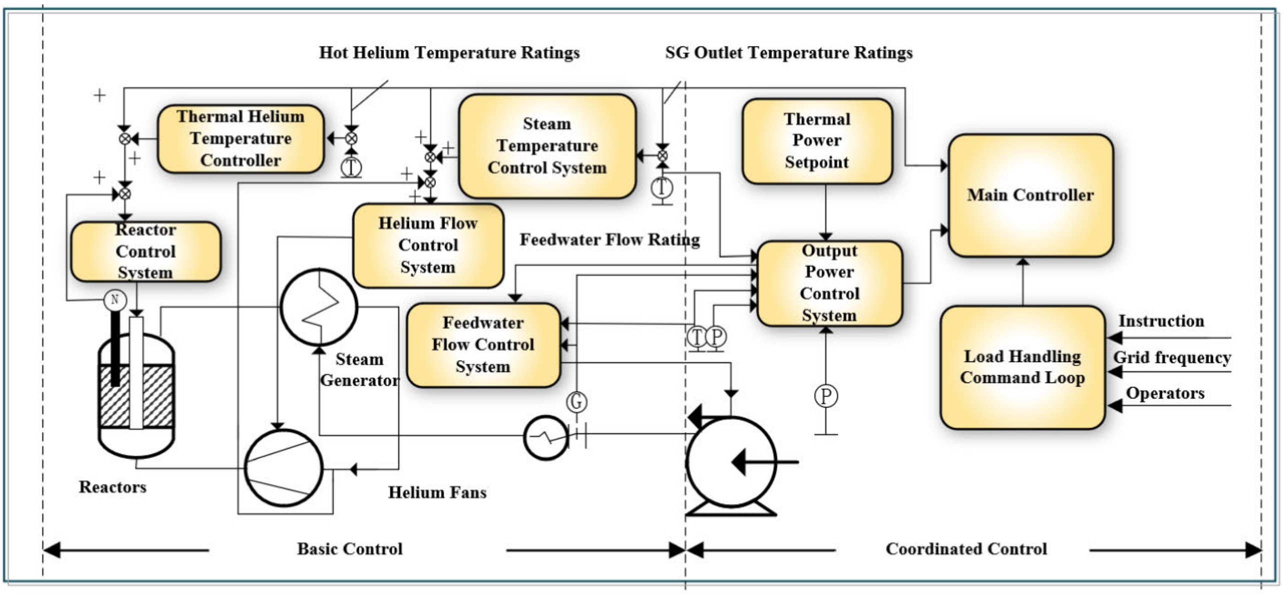

FIGURE 10. High-temperature gas-cooled reactor control structure.

options for desalination: first, using the condensate (steam) from the HTGR after power generation as a heat source to produce fresh water through a low-temperature multi-effect steam-filled desalination unit; second, a desalination program that directly uses steam from the steam generator outlet or draws steam from the turbine, i.e., part of the steam is used for desalination and part of the steam is used for power generation from the turbine generator; third, the electrical energy generated by the HTGR power plant, in addition to the reserved plant electricity, the rest of the electricity is used to drive the reverse osmosis membrane desalination unit to produce fresh water.

HTGRs can be used to improve the efficiency and recovery of thick oil extraction by heating and viscosity reduction of thick oil with its generated steam or thermal oil [188], while its generated steam or syngas can be used to liquefy or gasify coal to prepare liquid fuels or synthetic natural gas [189].

F. POWER SYSTEM IMPACT

HTGRs can provide thermal energy for the production of secondary energy sources such as synthetic fuels, methanol, and hydrogen, thereby reducing dependence on fossil energy sources and protecting the global environment from the greenhouse effect and acid rain caused by carbon dioxide emissions [190].

HTGRs have excellent inherent safety, i.e., there is no possibility of core meltdown and release of large amounts of radioactive material under any circumstances, and there is no significant impact on the public and the environment, thus reducing the threat to the stability and reliability of the power system. Reference [177] gives a detailed description of the safety characteristics of HTGR against hydrogen explosion, the safety characteristics against the release of fission products, and the safety characteristics for accident management. Reference [191] gives the conceptual design of the HTR-PM600, which uses six reactor modules and a steam turbine to form a nuclear power plant, and describes its features in terms of nuclear island layout, low-pressure vessel, safety analysis.

HTGRs have flexible operating performance, allowing power regulation according to power demand, and are coupled with renewable energy sources such as wind and solar to improve the peaking capability and economy of power systems, resulting in a stronger microgrid. Reference [192] analyzed the characteristics of combined cycle power generation systems based on HTGR, including thermodynamic performance, economic performance, and environmental impact, and compared them with other power generation systems.

VI. CONCLUSION

In conclusion, this paper has presented a comprehensive exploration of SMRs, namely LWR, LMR, MSR, and HTGR. It has examined deeply into their design, modeling, simulation, control, applications, and the impact they have on power systems. SMRs offer numerous advantages when compared to conventional large-scale reactors. Each type of SMR prioritizes compactness, incorporates enhanced safety features, and focuses on scalability, granting greater adaptability and flexibility across various settings. Utilizing advanced modeling techniques, such as CFD and simulations involving neutron transport and interaction, researchers can make precise predictions about the behavior of SMRs and optimize their performance.

Control systems play a vital role in guaranteeing the safe and efficient operations of SMRs. To regulate the parameters of the reactor, maintain power output, and adapt to changing conditions, advanced control algorithms like PID control and fuzzy logic control are employed. By employing these control strategies, the overall safety, stability, and dependability of SMRs are improved.

In addition, SMRs have diverse applications across various sectors such as power generation, space power, submarine and icebreaker development, thick oil extraction, and seawater desalination. Their compact and modular design makes them adaptable for on-grid and off-grid situations, allowing for energy production in a wide range of environments. SMRs have the potential capability to facilitate the shift towards a low-carbon future by offering a sustainable and dependable source of clean energy.

In summary, the study of SMRs has demonstrated their capabilities in terms of design, modeling, simulation, control, and applications. Further exploration and development in these domains will enhance the performance and implementation of SMRs, establishing them as a significant contributor to the worldwide energy equation. By utilizing their small size, safety features, and versatile applications, SMRs can facilitate the development of a more environmentally friendly energy future.

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