

## Discussion on Main Parameter Design of Small Pressurized Water Reactors

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### Abstract

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### Full Text

## Discussion on Main Parameter Design of Small Modular Pressurized Water Reactors

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## Abstract

Among the various types of Small Modular Reactors (SMRs), Small Modular Pressurized Water Reactors (SMPWRs) demonstrate unique advantages due to their mature technological foundation and flexible deployment capabilities, playing an increasingly important role in the future development of nuclear energy. This paper focuses on the overall design scheme and main parameter design of SMPWRs, systematically summarizing the design methodologies for the reactor core, reactor coolant system, and steam-side parameters, with particular emphasis on the influence of different core circulation modes on the overall scheme and main parameter design. The research employs a combined approach of theoretical analysis and simulation verification, proposes a main parameter design scheme for a natural circulation small PWR, and validates its feasibility through modeling and simulation. This paper provides ideas and recommendations for the subsequent research and development of SMPWRs, highlighting the advantages of natural circulation design in terms of safety and efficiency, which can serve as an important reference for future nuclear energy technology development.

**Keywords:** Small Modular Pressurized Water Reactor; Main Parameter Design; Forced Circulation; Natural Circulation; Simulation Validation

**Classification:** TL351

## Introduction

Small Modular Reactors (SMRs), hereinafter referred to as small reactors, are nuclear power plants with an electric power output not exceeding 300 MW. Compared with traditional large commercial pressurized water reactors, small reactors achieve modular design, modular prefabrication of equipment systems, and modular on-site assembly construction, offering numerous advantages such as high site adaptability, low investment risk, and short construction cycles[1]. In terms of safety, the simple structure of small reactors enables the practical elimination of various accidents, and their small radioactive source term reduces the probability of large-scale radioactive releases. Small reactors can complement large-scale nuclear power and represent an important future direction for global nuclear energy development. Among the various small reactor technologies, small pressurized water reactors (PWRs), with their high technological maturity, extensive operational experience, and strong deployment capabilities, are expected to become one of the first small reactor technologies to be deployed in batches[2].

Numerous studies have been conducted domestically and internationally on main parameter design schemes for small PWRs. LI Dongpeng et al.[3] investigated the matching relationships between main core parameters for annular fuel small PWRs. LIU Yusheng et al.[4] surveyed typical design parameters of floating small reactors in various countries and studied the thermal-hydraulic verification capabilities of small reactor cores under marine conditions. HAO

Chengming et al.[5] examined the variation patterns of thermal-hydraulic parameters in PWRs under natural and forced circulation. However, existing research has been limited to the core or reactor coolant system, with relatively few studies on the overall scheme of small PWRs, particularly lacking systematic engineering research on the integrated design of core, primary loop, and steam-side parameters.

Currently, most small PWR developments are still ongoing. Conducting methodological research on comprehensive main parameter schemes for small PWRs is of significant importance for their research and development design. This paper summarizes the overall technical schemes of small PWRs developed domestically and internationally, proposes a main parameter design methodology for small PWRs, and conducts in-depth research on the differences between forced and natural circulation core main parameter designs. This paper can provide ideas and recommendations for the subsequent development of small reactors.

## 1 Main Technical Characteristics of Small Reactors

The primary loop of large PWRs involves major components such as steam generators, main coolant pumps, and pressurizers, interconnected through main piping. In contrast, small reactors have low core thermal power, enabling heat transfer circulation within the pressure vessel and facilitating the formation of a highly integrated integral reactor structure. Integral reactors install main components directly inside the pressure vessel, eliminating interconnecting piping between components. This simple and compact structural design enables the practical elimination of numerous design basis accidents, significantly enhancing plant safety while substantially reducing site selection difficulty and construction costs.

Due to their large core power, large PWRs require substantial coolant flow to remove heat from the core, making forced circulation by main coolant pumps essential for the primary loop. Small PWRs, however, have low core power and can theoretically rely on natural circulation to remove core heat. Natural circulation small PWRs typically use the core as the heat source and the steam generator as the heat sink, relying on the driving head generated by fluid density differences between hot and cold legs to propel coolant flow through the closed loop. The establishment of natural circulation does not depend on main coolant pumps, offering several advantages: first, it significantly reduces the number of pipes and components, eliminating failures caused by main pump failure at the source; second, it reduces dependence on external power sources, greatly enhancing plant reliability under loss-of-power conditions. Additionally, natural circulation small reactors are easier to design as integral systems since they do not require main coolant pumps. In comparison, integral PWRs employing forced circulation must accommodate main coolant pumps. Fully integrated internal pumps still need to overcome technical challenges such as high-temperature bearings and electromagnetic coils, while external or insertable pumps create penetration interfaces between the pressure vessel and external equipment at

pump locations, preventing complete integration.

In recent years, many countries have been committed to developing small reactors with good safety performance and strong economic competitiveness, primarily for power generation, district heating, seawater desalination, and other applications. Representative foreign small reactors include B&W's mPower and NuScale's NuScale designs, while China's representatives include the ACP100 modular small PWR developed by China National Nuclear Corporation and the NHR low-temperature heating reactor designed by Tsinghua University[6]. The mPower and ACP100 employ forced core circulation designs, whereas NuScale and NHR adopt natural core circulation designs, each with its own advantages and disadvantages.

## 2 Introduction to Main Parameters of Small PWRs

Main parameters are those that significantly impact nuclear power plant operation and safety, representing the advanced level of design indicators such as safety, operability, and economics. The core differences between different reactor models lie in their main parameters. Nuclear power plant main parameters can be divided into four categories:

- a) User requirement parameters, which are typically determined based on user needs or local regulatory requirements and can be subdivided into:
  - Plant performance level: including rated power output, design life, availability, etc.;
  - Plant safety level: including safe shutdown earthquake, core damage frequency, large release frequency, etc.;
  - Plant control level: including operator non-intervention time, core control mode, etc.;
  - Plant operation and maintenance level: including collective worker dose, annual generation of radioactive solid waste, etc.
- b) Core parameters, which characterize the overall core design scheme and mainly include core thermal power, fuel assembly type and quantity, linear power density, core inlet/outlet temperature, enthalpy rise factor, etc.
- c) Primary loop parameters, which characterize the overall primary loop design scheme and mainly include primary loop flow rate, pressure, temperature, and other related parameters.
- d) Secondary loop parameters, which characterize the overall steam-side design scheme and mainly include steam pressure, steam temperature, steam flow rate, steam moisture, feedwater temperature, feedwater flow rate, etc.

## 3 Core Parameter Design of Small PWRs

Typically, the plant's rated output (electric power) serves as one of the primary project development objectives and must be determined first. Based on the

thermal efficiency of the Rankine cycle, the core thermal power value can be derived. Because the secondary side temperature and pressure of small PWRs are often lower than those of large PWRs, making it difficult to design multiple reheating stages in the secondary loop, the thermal efficiency of small PWRs usually does not exceed 35%.

After determining the core thermal power, preliminary judgments can be made regarding the number and type of fuel assemblies. Truncated fuel rods are one of the most common fuel assembly types for small PWRs, although some reactors may also employ other types such as box-type fuel assemblies. Since the core must adopt a square,  $1/8$  symmetric arrangement, the number of assemblies per row,  $N$ , must satisfy the condition that “ $(N^2-1)$  is divisible by 8.” Table 1 presents common core fuel assembly arrangements.

#### **Table 1 Common Arrangement of Core Fuel Assembly**

Small PWRs have relatively low core thermal power. To reduce the length and diameter of the pressure vessel, they typically employ truncated fuel assemblies with  $7 \times 7$  or  $9 \times 9$  core fuel arrangements. After determining the fuel assembly arrangement, iterative calculations and verification must be performed in conjunction with reactor physics design for parameters such as core linear power density, enthalpy rise factor  $F\Delta H$ , and hot spot factor  $F_q$ .

### **4 Primary Loop Thermal-Hydraulic Parameter Design of Small PWRs**

Primary loop thermal-hydraulic parameter design reflects the thermal-hydraulic characteristics of the primary loop, among which temperature, pressure, and flow rate are the most critical parameters. Table 2 presents partial main parameters of four representative reactor types.

#### **Table 2 Main Design Parameters of Typical SMRs**

Among the three temperature parameters—inlet temperature, outlet temperature, and average temperature—the core outlet temperature is the highest and most constraining parameter for core thermal-hydraulic design. Increasing the core outlet temperature is beneficial for improving secondary loop steam quality, thereby enhancing plant efficiency and economics. Currently, most PWR fuel assemblies use zirconium alloys. Constrained by the maximum tolerable temperature of zirconium alloys at  $350^\circ\text{C}$ , the core outlet temperature is typically kept below  $350^\circ\text{C}$  with an appropriate margin. This margin is the core subcooling, which can maximally limit core boiling during accident conditions.

Core heat must be transferred outward through primary loop coolant, typically characterized by the flow-to-power ratio (the ratio of core flow rate to thermal power), which represents the coolant flow required to transfer unit heat. The flow-to-power ratio is inversely proportional to the enthalpy difference between core inlet and outlet. A smaller flow-to-power ratio means less core flow, potentially leading to insufficient heat removal capability and reduced safety. A

larger flow-to-power ratio means greater driving force required, increasing the difficulty of engineering design and equipment selection. Therefore, the flow-to-power ratio should be within a reasonable range. It should be noted that the flow-to-power ratio also affects core inlet and outlet temperatures.

The selection of the flow-to-power ratio is related to the primary loop circulation mode. Natural circulation has weaker driving force and thus smaller flow, making it difficult to achieve a flow-to-power ratio higher than 5 g/J with current equipment manufacturing capabilities. If a natural circulation scheme is adopted, reasonable hot and cold temperature differences and elevation differences must be selected, and primary loop flow resistance must be estimated to ensure successful establishment of natural circulation with the flow-to-power ratio within a reasonable range. For forced circulation, coolant is driven by main coolant pumps, and core flow can be adjusted by regulating pump output. However, an excessively large flow-to-power ratio increases the burden on main pumps and reduces economics. Therefore, the flow-to-power ratio is generally controlled between 5 g/J and 8 g/J to better balance safety and economics.

## 5 Secondary Loop Parameter Design of Small PWRs

The main function of the nuclear power plant's secondary loop is to receive heat transferred from the primary loop coolant and generate steam. As the heat sink for the primary loop during normal operation, the secondary loop must remove heat generated by the core. Simultaneously, the secondary loop must produce high-quality steam to drive the turbine.

The main factors constraining main steam parameters are threefold: first, the temperature of primary loop coolant, as main steam temperature typically does not exceed that of the heat source; second, the requirements of the turbine-generator set for main steam quality; and third, the size and manufacturing level of the steam generator. Due to strict domestic highway transportation requirements for large objects, the size of steam generators for modular small reactors is constrained. Additionally, plants typically require approximately 20°C superheat for main steam. Currently, small PWR secondary side pressure usually does not exceed 5 MPa, main steam temperature typically does not exceed 290°C, and main feedwater temperature can be appropriately selected based on these two parameters. Once the steam generator type is selected, other secondary loop parameters can be calculated based on energy conservation.

## 6 Main Parameter Design Process for Natural Circulation Small Reactors

Based on the design methodology mentioned above, this paper proposes a potential main parameter design scheme for a natural circulation small PWR, using the NHR small PWR as a reference, and conducts simulation analysis to verify the feasibility of the methodology.

In the proposed scheme, the core adopts the same configuration as NHR, i.e., a  $9 \times 9$  fuel arrangement, with a reactor power of 200 MW and an operating pressure of 80 bar. When designing primary loop parameters, a suitable flow-to-power ratio is first selected based on engineering experience (approximately 4.5 g/J in this paper), from which a core flow rate of approximately 900 kg/s can be obtained. Since the flow-to-power ratio is the inverse of the enthalpy difference between core inlet and outlet, and given known primary loop pressure and average temperature, the enthalpy difference can be derived from the flow-to-power ratio, and subsequently the core inlet and outlet temperatures can be determined. With known elevation difference between core inlet and outlet, the natural circulation driving head can be further obtained. If this driving head exceeds the primary loop resistance, natural circulation can be established.

Since secondary loop parameters are significantly influenced by steam generator selection and require numerous assumptions that are difficult to generalize, this paper does not present specific case studies for the secondary loop.

To verify the engineering feasibility of the above parameters, this paper developed a thermal-hydraulic parameter analysis model covering the main components of the core and primary loop using the Modelica modeling language, and performed steady-state simulations. The simulation results demonstrate that when the natural circulation driving head exceeds primary loop resistance, natural circulation in the primary loop can be successfully established, and main parameters such as pressure, flow rate, and temperature can reach stable states close to the design values. Detailed results are presented in Table 3. Figure 1 [Figure 1: see original paper] illustrates the process of main parameters varying with time and reaching stability. The simulation results preliminarily validate the feasibility of this natural circulation small reactor main parameter design scheme.

**Table 3 Engineering and Modeling of Main Parameters**

**(a) Core pressure and mass flow reaching steady state**

Parameter	Engineering Derivation Method	Design Value	Simulation Result
Core power /MW	Initial assumption		
Coolant pressure	Initial assumption		
Flow to power ratio $/(g \cdot J^{-1})$	Initial assumption		

Parameter	Engineering Derivation Method	Design Value	Simulation Result
Core average temperature/°C	Initial assumption		
Core mass flow/(kg · s <sup>-1</sup> )	Derived from		
Core inlet temperature/°C	Derived from		
Core outlet temperature/°C	Derived from		
Core height /m	Initial assumption		
Driving head /kPa	Derived from , compared with drag force		

### (b) Inlet and outlet temperature reaching steady state

#### Figure 1 [Figure 1: see original paper] Main Parameters' Curves

This paper focuses on the overall scheme and main parameter design of small PWRs. The main parameters of small PWRs include core parameters, primary loop parameters, and steam parameters. The primary loop can adopt either natural circulation or forced circulation modes, with different overall layout schemes and main parameter selection methods for each circulation mode. This paper provides recommendations on core fuel assembly arrangement, primary loop flow-to-power ratio selection, and secondary loop steam parameter selection for small PWRs, and demonstrates and validates the design process for primary loop parameters of natural circulation small reactors. Currently, the vast majority of small PWRs are still in the conceptual development stage, and this paper can provide ideas and recommendations for the research and development design of new small reactors.

### References

- [1] CHEN Wenjun, JIANG Shengyao. Feasibility Study on Developing Small Reactor Nuclear Energy Systems in China[J]. Nuclear Power Engineering, 2013, 34(2): 153-156.

- [2] IAEA-TECDOC-1485 Status of Innovative Small and Medium Sized Reactor Designs, Vienna: International Atomic Energy Agency, 2005.
- [3] LI Dongpeng, ZHU Qingfu, XIA Zhaodong. Design of 330MW Annular Fuel Small Reactor[J]. Atomic Energy Science and Technology, 2020, 54(10).
- [4] LIU Yusheng, WU Peng, LIU Xirui, et al. Analysis of Thermal-Hydraulic Verification Capability for Floating Small Reactor Core[J]. Nuclear Safety, 2020, 19(5).
- [5] HAO Chengming, FU Wen, PENG Minjun, et al. Transient Characteristics Analysis of Integral Reactor During Forced to Natural Circulation Transition[J]. Atomic Energy Science and Technology, 2013, 47(2): 243-248.
- [6] LIU Xiaozhuang. Comparative Analysis of Safety Characteristics of Domestic and Foreign Small PWRs[J]. Nuclear Safety, 2015, 14(1): 56-59.

*Note: Figure translations are in progress. See original paper for figures.*

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