# The Main Reason of SG Thermal Power Imbalance Between Each Loop in CPR1000 Nuclear Power Plants

Chao-hao Shang[1,3](✉), You-sen Hu[1], Yuan-xiong Guo[2], Chang-ying Li[1], and Jun Chen[1]

[1] China Nuclear Power Technology Research Institute, Shenzhen 518038, Guangdong, China
shangchaohao@126.com
[2] Daya Bay Nuclear Power Operation and Management Co., Ltd., Shenzhen 518124, Guangdong, China
[3] Research on Reactor Thermal Hydraulic, Safety Analysis and Technical Support for PWR Operation, China Nuclear Power Technology Research Institute, Shenzhen, Guangdong, China

**Abstract.** The SG thermal power imbalance between each loop exists in some CPR1000 nuclear power plants. In this paper, the authors trying to figure out the chief reasons of SG power imbalance between each loop by analyzing the measurement data from the Nuclear Power Plants. The main thermal parameters from the nuclear power plants are analyzed. By analyzing factors affecting the SG thermal power, the main factors affecting the SG thermal power are loop flowrate and hot leg temperature. The loop flowrate depends on the pump characteristic curve and the loop resistance coefficient. The hot leg temperature depends on RPV structure and core power distribution. A CPR1000 SG model was established and the sensitivity analysis of the coefficients which affect SG heat transfer is performed. The analysis results show that the deviation of the hot leg temperature between loops has the most significant effect on the SG thermal power imbalance. Hence, the SG thermal power imbalance between each loop mainly due to the RPV structure, the core power distribution and the flowrate deviation.

**Keywords:** CPR1000 nuclear power plants · Power imbalance · RPV structure · Core power distribution · Asymmetric primary flowrate

## 1 Introduction

The alarm of 'Loop 1 SG Thermal Power Greater than 102%FP' was occurred in one CPR1000 Nuclear Power Plant during operation. The total reactor power is less than 100% FP when the alarm occurs. The core flowrate and each loop flowrate are both between the thermal design flow rate and the mechanical design flow rate, which means the flowrate does not exceed the criteria. The power measurement results show that there is a large deviation (almost 50MW) of SG thermal power between loops. Further investigation found that the SG thermal power imbalance between each loop exists in some CPR1000 nuclear power plants, especially when these power plants are operated


C. Liu (Ed.): PBNC 2022, SPPHY 283, pp. 231–242, 2023.
https://doi.org/10.1007/978-981-99-1023-6_22

in the transition cycles (from 12-month fuel management change to 18-month fuel management). This paper extracts a large number of measurement data from 13 CPR1000 nuclear power plants within total 27 cycles. The data mainly include SG thermal power, feedwater temperature, feedwater flowrate, SG steam pressure, primary loop flowrate, hot leg temperature, cold leg temperature etc. The trends of SG thermal power for two typical SG thermal power imbalance cycles in CPR1000 nuclear power plants are showed in Fig. 1 and Fig. 2.

The research in China mainly focuses on the flowrate imbalance between loops. ZHAO De-yuan [1] has analyzed the flow measurement deviation of the primary loop of Unit 2 in Ling'ao Nuclear Power plant, and provided the treatment measures. Wang Chuang [2] concluded that the single loop flowrate deviation mostly is caused by the measurement factors and nuclear power stations can carry out the fault analysis and confirmed by test and measurement data during the unit overhaul. LI Hua-sheng [3] concluded that loop flowrate deviation mostly is caused by resistance characteristics and pump characteristics. Liu Jianquan [4] made an analog study on the influence of loop flow deviation on enthalpy rise characteristics of the units. Some research on the influence of pipe blockage on safety analysis in Steam generator also has been carried out [5, 6].

This paper trying to figure out the main reason of SG power imbalance between loops in CPR1000 Nuclear Power Plants by measuring data analysis and quantitative calculation.

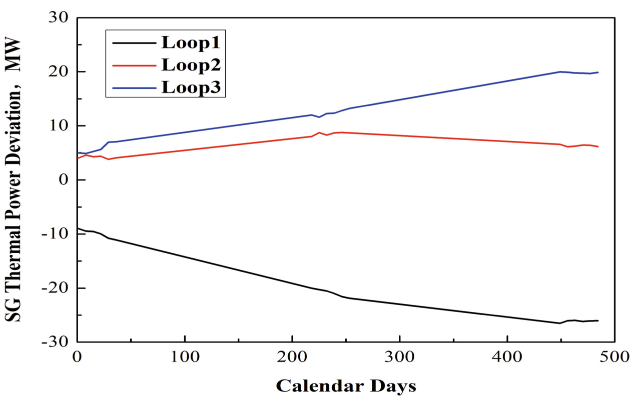



**Fig. 1.** Relationship between thermal power deviation and calendar days in typical cycle 1

## 2 Root Cause Analysis

According to the source of the deviation, the reason of SG thermal power imbalance can be divided into measurement factors and actual deviation. The analysis flow chart is shown in Fig. 3.

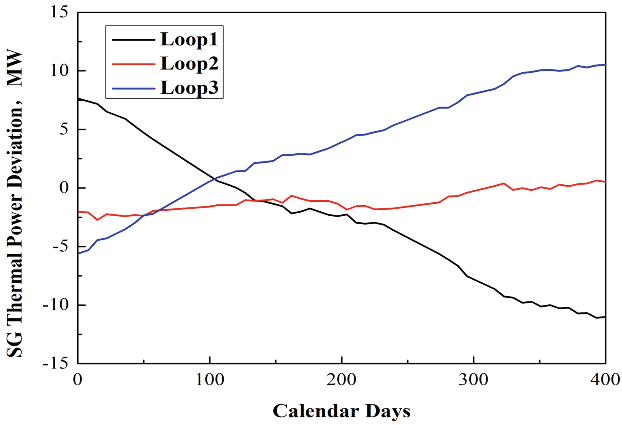



**Fig. 2.** Relationship between thermal power deviation and calendar days in typical cycle 2

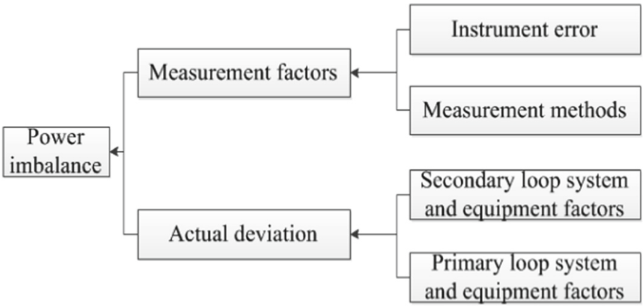



**Fig. 3.** The source of the SG thermal power imbalance

## 2.1 Measurement Factors

The measurement factors consist of the following two parts:

(1) Measurement uncertainty. Mainly refers to the uncertainty during the parameter measurement process. The uncertainty of each SG thermal power measurement is about 0.87% in CPR1000. So the maximum uncertainty of the thermal power deviation between loops is about 1.23% (nearly 12 MW). If the SG thermal power imbalance between each loop is less than 12 MW, the SG thermal power imbalance is considered to be within the measurement uncertainty.

(2) Measurement method. Due to instrument limitations, the blowdown flowrate of each SG can't be measured separately in CPR1000. The calculation of SG thermal power assumes that the three SG blowdown flowrate are equal. In fact, the blowdown flowrate between three SG can't be consistent. This may introduce some error. However, the blowdown flowrate is only 1% of the feedwater flowrate. So the error caused by the measurement method is very small.

Taking into account that the CPR1000 units are using the same measurement system, each unit shall be calibrated regularly according to the regulations, the measured SG power is credible.

Hence, the power deviation is realistic. The root cause analysis are performed based on the data from two typical cycles. Additional measured data in these two cycles are provided in Fig. 4 and Fig. 5.

## 2.2 Actual Deviation

Power deviation can be classified into two parts: primary circuit deviation and secondary circuit deviation.

### 2.2.1 Secondary Circuit Factors

The thermal power of the secondary circuit is calculated by the following formulas:

$$\mathrm{W_{SG} = Q_s \cdot x \cdot H_s + Q_s \cdot (1 - x) \cdot H_{sat} + Q_b \cdot H_{sat} - Q_{fw} \cdot H_{fw}}$$
$$\mathrm{Q_s + Q_b = Q_{fw}}$$

where:

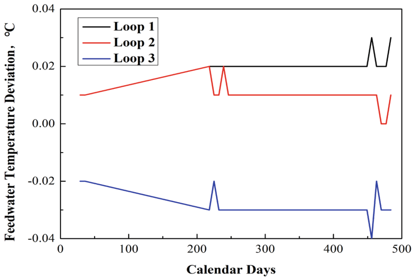
$W_{SG}$: SG thermal power.
$Q_s$: SG steam flowrate.
$x$: Steam quality.
$Q_b$: blowdown flowrate.
$Q_{fw}$: feedwater flowrate.
$H_s$: Steam enthalpy.
$H_{sat}$: blowdown enthalpy.
$H_{fw}$: feedwater enthalpy.

(1) Feedwater Temperature

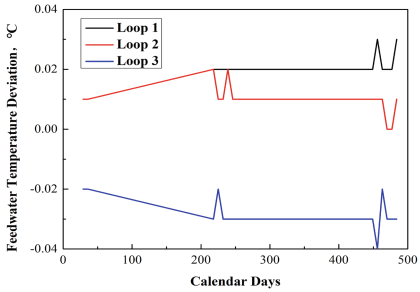
The difference in feedwater temperature between loops is small. The deviation of the feedwater temperature between each loop is generally within 0.1 °C. The main causes of feed water temperature difference are heat dissipation, flow resistance and other factors. The slight difference of feed water temperature has little effect on SG thermal power imbalance.

(2) Steam Pressure

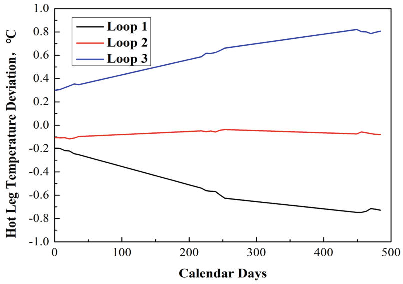
There is little difference in steam pressure between loops, because steam from each loop will converge into the steam header. The deviation of the steam pressure between each loop is generally within 0.01 MPa. Assuming that the steam pressure deviation is 0.05 MPa, the change of steam enthalpy is less than 0.025%. This deviation leads to the imbalance of SG thermal power less than 0.23 MW. Therefore, the influence of steam pressure deviation on thermal power imbalance between circuits can be ignored.



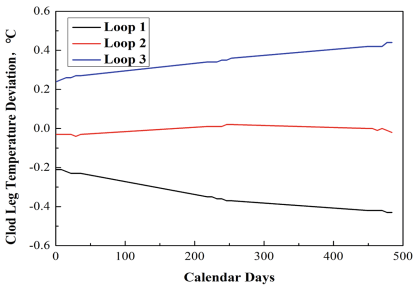

a) Feedwater Flowrate




b) Feedwater Temperature

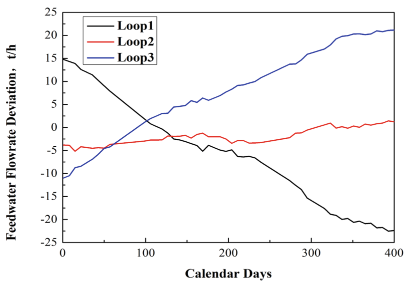



c) Hot Leg Temperature

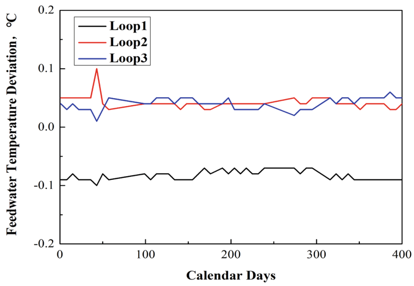



d) Clod Leg Temperature

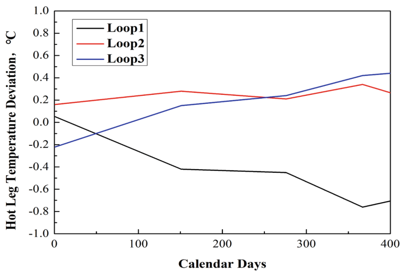
**Fig. 4.** Main thermal parameters in typical cycle 1



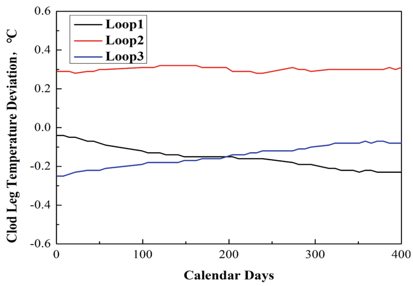

a) Feedwater Flowrate




b) Feedwater Temperature




c) Hot Leg Temperature




d) Clod Leg Temperature

**Fig. 5.** Main thermal parameters in typical cycle 2

(3) Steam Quality

According to experience feedback, there is no obvious change in steam quality. If the steam humidity deviation between each loop is 0.1%, the steam enthalpy difference caused by steam humidity deviation is about 0.55%, and the influence on SG thermal power imbalance is about 0.54 MW. Therefore, the influence of steam quality deviation on thermal power imbalance between circuits can be ignored.

(4) Feedwater Flowrate (Steam Flowrate)

It can be seen from the variation trend of SG thermal power and feedwater flowrate that the variation trend of these parameters is highly consistent. This is because there is little difference in other parameters affecting thermal power among circuits. Therefore, the SG thermal power is substantially linearly related to the feedwater flowrate (steam flow rate). According to the characteristics of the Steam generator, the steam flowrate depends on the heat transfer in the primary circuit. Feedwater flowrate control program is applied to regulating flow rate to match with steam flowrate and keep SG water level stable. Therefore, the feedwater flowrate (steam flow rate) is affected by SG heat transfer. The influencing factors of SG heat transfer performance and primary circuit need further analysis.

(5) SG heat Transfer Performance

At present, no direct data can prove the heat transfer capability between Steam generators. Considering that CPR1000 nuclear power plant has not been in operation for a long time, and there is no pipe blockage in SGs, the heat transfer capability of SG is expected to be sufficient. Therefore, it is considered that the difference of heat transfer capability of SG is not the main factor causing the thermal power imbalance between loops.

(6) Summary

According to the previous analysis, the influence of feed water temperature deviation, steam pressure deviation and steam quality deviation on SG thermal power imbalance can be ignored. The deviation of feedwater flowrate is caused by SG heat transfer imbalance. The heat transfer of SG is directly affected by the state parameters of the primary circuit, so it is necessary to analyze the state parameters of the primary circuit.

### 2.2.2 Primary Circuit Factors

The thermal power of the primary circuit is calculated by the following formula:

$$W_{SG} = Q_{loop} \cdot (H_h - H_c) + W_o$$

where:

$W_{SG}$: SG thermal power.

$Q_{loop}$: loop flowrate.
$H_h$: hot leg enthalpy.
$H_c$: cold leg enthalpy.
$W_o$: Other heat sources except the core transfer to RCP.

(1) Loop Flowrate

The difference of loop flowrate will directly affect the SG heat transfer capability. The results of loop flow measurement test (RCP64) show that there are differences in loop flowrate. The flow rate of each loop is determined by the characteristics of the pump and the resistance characteristics of the primary circuit. For the resistance characteristics of the primary loop, the core and upper chamber in the Reactor pressure vessel are not strictly symmetrical relative to three loops. Thus, the resistance characteristics of the three loops are different. For the characteristics of the pump, the design is the same, but it may be slightly different in manufacture and installation. In the base load operation condition, the output of Primary pump remains basically unchanged. Therefore, the loop flowrate contributes to the initial deviation of thermal power between loops, but it is not the cause of the change of thermal power deviation between loops during operation.

(2) Primary Circuit Temperature

The measurement data shows that there are significant differences in the hot leg temperature and the old leg temperature among different loops. The temperature deviation of hot legs is about 0.8°C, and the maximum is more than 1.6 °C. The temperature deviation of cold legs is within 0.5 °C, and the maximum is less than 0.8 °C. Because the temperature deviation of cold leg is smaller than that of hot leg. The deviation of hot leg temperature will lead to the deviation of average temperature between loops, which will change the heat transfer of each SG and further lead to the deviation of SG thermal power.

(3) Hot Leg Temperature

From the direction of coolant flow, the coolant is heated by the core and then flows to SG for heat transfer. Hot leg temperature is mainly affected by core power distribution and mixing capacity in the upper plenum. In the RPV structure design, the core and the upper plenum are 1/4 symmetrical, and the loops are 1/3 symmetrical. The asymmetry of this structure will cause the difference of core area corresponding to each loop. Meanwhile, the time of the coolant flows through the upper plenum is very short, the mixing effect of the upper plenum is limited. The coolant at the different assembly's outlet will directly flow to the loop which the assembly is closer to. This phenomenon makes it difficult for coolant to mix in the upper plenum area, which leads to the difference of temperature in the hot leg of each loop. Therefore, due to the asymmetry of core power distribution corresponding to the three loops, the core outlet temperature corresponding to the three loops is different. The coolant does not mix well in the upper plenum area, which leads to the hot leg temperature deviation between the loops. During power operation, the change of core power distribution will further lead to the change of hot section temperature during the cycle.

(4) Summary

The flow deviation of the three loops caused by RPV structure factors (resistance characteristic difference between loops) and primary pump output will bring the initial thermal power deviation of the unit, but the deviation generally remains stable during operation. The core power distribution (asymmetry corresponding to the three loops) and RPV structure factors (asymmetry between the loops and the core, uneven mixing in the upper plenum area) lead to the hot leg temperature difference between the loops. These are the main factors that affects thermal power imbalance in primary loop.

### 2.3 The Influence of Core Power Distribution on Hot Leg Temperature

In order to analyze the influence of core power distribution on hot leg temperature, a core sub-channel model and an upper plenum CFD model are established to calculate hot leg temperature. The analysis model is shown in Fig. 6.

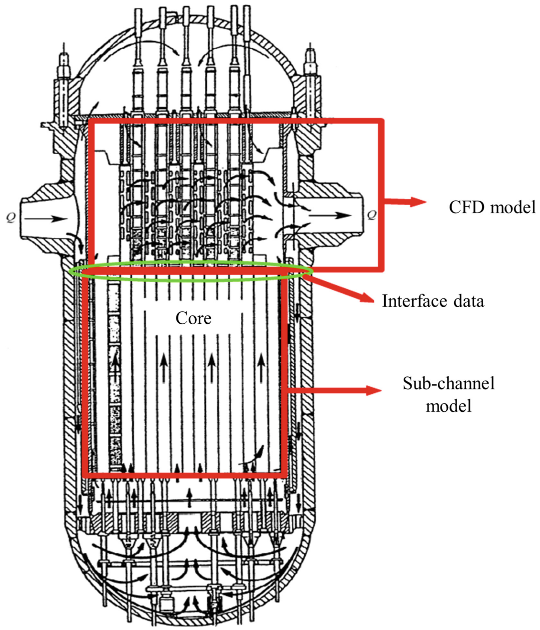



**Fig. 6.** Schematic diagram of analysis model

#### 2.3.1 Core Sub-channel Model

The core sub-channel model consists of 157 sub-channels. Each channel corresponds to one Fuel assembly. The core power distribution and thermal parameters are used as inputs of the model. The flow rate and temperature of each Fuel assembly can be calculated by changing the core power distribution under different Burn-ups. The results are provided as interface parameters to the upper plenum CFD model to carry out the hot leg temperature calculation.

### 2.3.2 The Upper Plenum CFD Model

A lot of research have been carried out on the upper plenum CFD model [7–9]. In this paper, the structure of the upper plenum is modeled in detail with reference to the relevant analysis experience. The STAR CCM + code is used for the analysis. The area of the CFD model is shown in Fig. 7, and the CFD meshing result is shown in Fig. 8. The total grid of the whole CFD model is 28.48 million. The inlet boundary conditions of the model are core outlet velocity and temperature, and the hot leg outlet boundary condition is set to the pressure boundary.

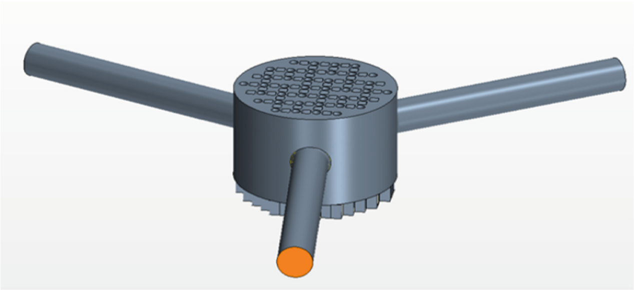


**Fig. 7.** CFD model domain

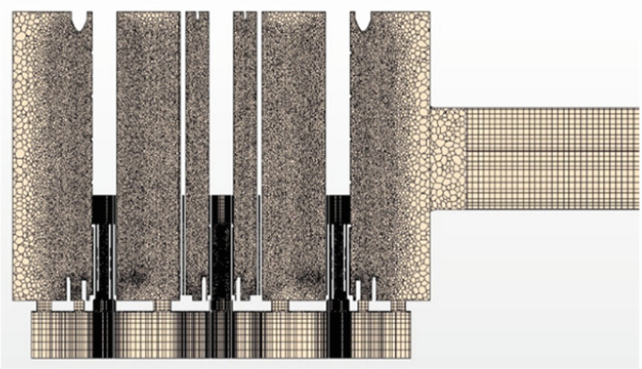


**Fig. 8.** Mesh generation

### 2.3.3 The Hot Leg Temperature Analysis Result

Based on the power distribution of two typical cycles, the hot leg temperature is calculated by analysis model, the calculated results are shown in Fig. 9 and Fig. 10. It can be seen from the calculation results that the variation trend of hot leg temperature is in good agreement with the actual variation trend. This further proves that the variation of hot leg temperature during the cycle is caused by the variation of core power distribution.

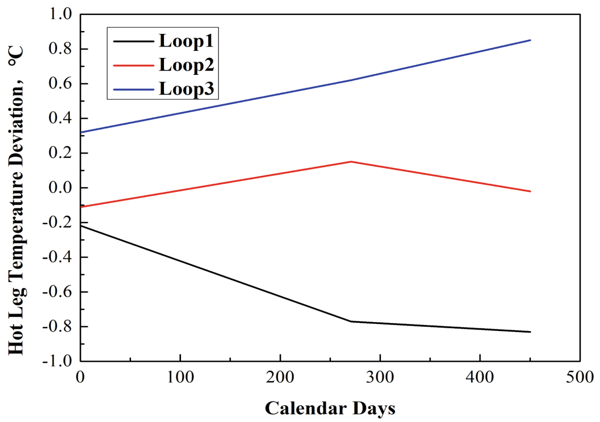



**Fig. 9.** Hot leg temperature result of typical cycle 1

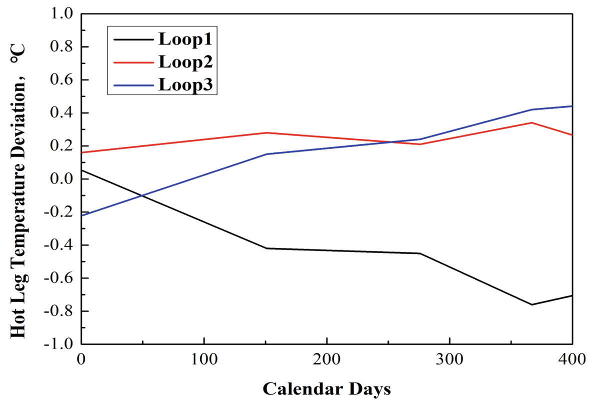



**Fig. 10.** Hot leg temperature result of typical cycle 2

## 3 Weight Sensitivity Analysis

The sensitivity analysis of the main factors affecting the thermal power imbalance between loops is carried out in this chapter. These analyses try to find out the weight of each influencing factor. Through the analysis, the main factors affecting SG thermal power imbalance are: hot leg temperature and loop flow rate. The CPR1000 SG model was established by CGN in house code LOCUST. Sensitivity analysis of hot leg temperature and loop flowrate was carried out respectively.

The influence of these parameter changes on SG thermal power is shown in Fig. 11. It can be seen from the calculation results that the influence of each parameter on SG thermal power is different. The influence of hot leg temperature on SG thermal power is more significant.

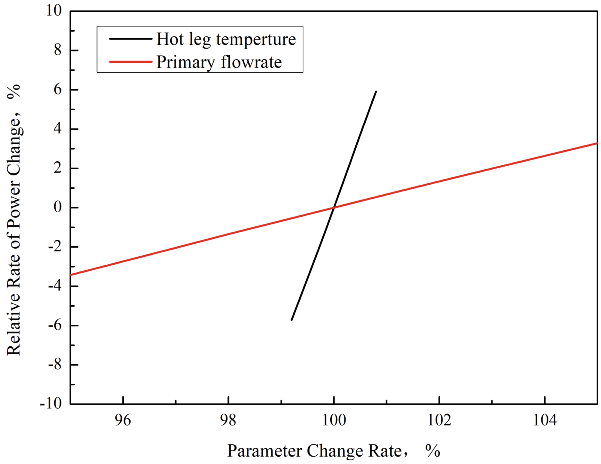



**Fig. 11.** The corresponding relationship between parameters and SG thermal power

## 4 Conclusion

Based on the measured data and a core sub-channel coupled with CFD analysis model, this paper analyzes the causes of thermal power deviation between loops, and deduces that the main reasons affecting the power deviation between loops are the difference of loop flow and hot leg temperature. Weight sensitivity analysis shows that hot leg temperature deviation has more significant effect on thermal power deviation.

The flow deviation of the three loops are caused by RPV structure factors (resistance characteristic difference between loops) and primary pump output, which will bring the initial thermal power deviation of the unit, but the deviation generally remains stable during operation. The core power distribution (asymmetry corresponding to the three loops) and RPV structure factors (asymmetry between the loops and the core, uneven mixing in the upper plenum area) lead to the hot leg temperature difference between the loops. The main factor that causes the increase of thermal power deviation between loops during operation is the change of core power distribution.

## References

1. Zhao, D..-y.: Analysis of the discrepancies of reactor coolant flowrate measurement in unit 2 of Ling'ao nuclear power plant. Nucl. Power Eng. **25**(4), 373–376 (2004)

2. Wang, C., et al.: Fault mechanism analysis of single loop flow deviation in PWR nuclear power plants. Nucl. Power Eng. **35**(5), 117–119 (2014)
3. Li, H., et al.: Proposed solutions and root cause of the M310 type PWR licensee event on RCP loop flow and core total flow over the mechanical design flow limit. Nucl. Saf. **14**(4), 30–35 (2015)
4. Liu, J., et al.: Simulation study of enthalpy gain characteristics on nuclear power 1 000 MW unit pressurized water reactor loop flow deviation. Proc. CSEE **35**(16) (2015)
5. Pla, P., Reventos, F., Ramos, M.M., et al.: Simulation of steam generator plugging tubes in a PWR to analyze the operating impact. Nucl. Eng. Des. **30515**, 132–145 (2016)
6. Zhao, X., et al.: Three-dimensional study on the hydraulic characteristics under the steam generator (SG) tube plugging operations for AP1000. Prog. Nucl. Energy **112**, 63–74 (2019)
7. Li, X.-b., et al. : Analysis of coolant temperature fluctuating in upper plenum of PWR. Atomic Energy Sci. Technol. **46**(11) (2012)
8. Yu, P.-a., et al.: The experimental study on steady flow in PWR upper plenum. Chin. J. Nucl. Sci. Eng. **16**(1) (1996)
9. Wana, L., et al.: Numerical simulation of temperature heterogeneity inside the AP1000 upper plenum and hot leg. Nucl. Eng. Des. **362**, 110525 (2020)