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A Study On The Thermal Movement Of The Reactor Coolant System For PWR

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가압 경수로의 냉각재 계통 열팽창 거동에 관한 연구

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Abstract

The structural analysis of the reactor coolant system mainly consists of two fields. The one is the static analysis considering the impact of pressure and temperature built up during normal operation. The other is the dynamic analysis to estimate the impact of postulated events such as the seismic loads or postulated branch line pipe breaks event. Since the most important goal of the RCS structural analysis is to prove the safety of the RCS during normal operation or postulated events, a widely proven theory having enough conservatism is adopted. The load occurring on the RCS during normal operation is considered as the basic design loading condition throughout whole plant life time. The most typical characteristic of the RCS during normal operation is the thermal expansion of the RCS caused by reactor coolant with high temperature and pressure. Therefore, the exact estimation on the thermal movement of the RCS is needed to get more clear understanding on the thermal movement behavior of the RCS.

In this study, the general structural analysis concept and modeling method to evaluate the thermal movement of the RCS under the normal plant operation condition are presented. To discuss the validation of the suggested analysis, analysis results are compared with the measured data which were referred from the standardized 1000 MWe PWR plant under construction.

요 약

원자로냉각재계통의 설계를 위한 구조해석 분야에는 원자로의 정상운전 과정에서 발생하는 유체의 온도와 압력의 변화에 의해 냉각재계통에 발생하는 정적하중해석, 지진과 가상적인 분지관 파단사고에 의해 냉각재계통에 발생하는 동적하중해석분야로 구분할 수 있다. 원자로냉각재계통의 구조해석은 원자력

발전소의 안전성 확보 측면을 중시하여 해석시 충분한 여유도를 고려한 보수적인 해석 방법을 원용한다. 지진이나 가상적인 분지관 파단사고에 의한 냉각재계통의 구조해석은 사고시 냉각재계통의 안전성을 유지하는 방어적인 개념으로서 기기의 건전성을 확보하기 위하여 충분한 보수성과 안전여유가 해석시 고려된다. 정상운전에 의해 냉각재계통에 발생하는 하중은 원자력 발전소의 상존하는 하중의 개념으로서 냉각재계통의 기본 설계 하중으로 인식된다. 특히 고온 고압의 유체로 인하여 발생하는 냉각재 계통의 열팽창 현상은, 정상운전 하중으로 인하여 나타나는 전형적인 거동으로서, 냉각재계통 구조해석 결과의 중요한 지표로서 인식된다. 따라서 냉각재계통의 열팽창 현상을 정확히 예측하는 것은 원자로 냉각재계통 구조해석의 가장 중요한 목표중의 하나이다.

본 연구에서는 정상운전 하중에 의한 원자로 냉각재계통의 열팽창 거동을 해석하기 위한 냉각재계통의 모델링 방법과 해석 방법을 제시하였다. 해석 결과의 타당성을 검토하기 위하여 최근 건설 완료 단계에 돌입한 표준형 1000 MWe 급 가압경수로(PWR)의 고온기능시험(Hot Function Test)과정에서 실측한 자료를 근거로 하여 원자로냉각재계통의 열팽창 거동 해석의 타당성을 입증코자 하였다.

1. Introduction

The current standardized 1000 MWe PWR(Pressurized Water Reactor) reactor coolant system, hereafter referred as the RCS, has one reactor vessel, two steam generators,four pumps and piping systems constituting total two loops. The pressure of the RCS is maintained upto 2250psig at normal operation condition. The temperature of reactor coolant is 625°F before heat exchange in the steam generator and drops to 565°F after the heat exchange. The reactor vessel has four vertical support columns with horizontal gaps at the column flange for thermal expansion and is separated by the primary shield. Steam generators are mounted on each sliding support pad to allow the thermal expansion caused by the main coolant piping during heat-up or cool-down process. Upper and lower keys and hydraulic snubbers are designed to resist dynamic motions. Four vertical and four horizontal support columns support the reactor coolant pump (RCP) and two hydraulic snubbers are also employed to withstand dynamic motions. Main coolant pipings connect each reactor coolant component and constitute two independent loops. Fig. 1 shows a brief configuration of the RCS. The main purpose of structural analyses of the RCS is to produce the design basis loads for the RCS design for various plant conditions such as the seismic event, the normal operation condition, the postulated branch line pipe break condition, etc. High temperature of reactor coolant produces the thermal expansion of the RCS and corresponding loads on each component. Since the thermal expansion may reduce the size of gaps defined at support structures, the basic design feature of allowing the free thermal expansion should be maintained to ensure the integrity of the whole RCS structures. Therefore, the exact estimation of the thermal movements during the normal plant operation is one of the most important design procedures.

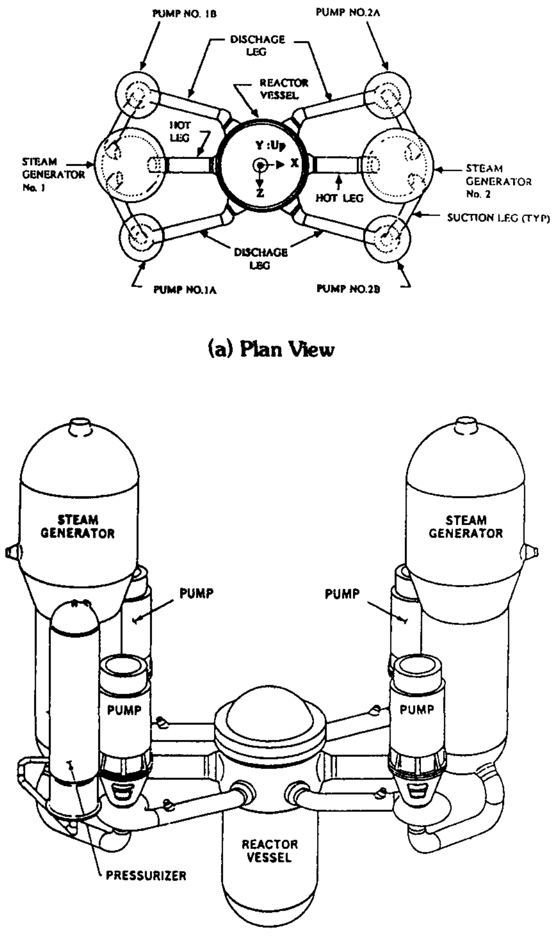
In this study, the general structural analysis concept and modeling method to evaluate the thermal movement of the RCS under the normal plant operation condition are presented. To discuss the validation of the suggested analysis, analysis results are compared with the measured data which were referred from the standardized 1000 MWe PWR plant under construction.

2. Structural Analysis of RCS

2.1. Basic Assumptions

The basic assumptions considered for RCS modeling and analyses are as follows.

1) Since the RCS consists of relatively stiff structures



(a) Plan View

(b) General Layout

Fig. 1. Configuration of Reactor Coolant System

such as pressure vessels, pipings and support structures, the typical linear elastic deformation theory is applied to expect the representative characteristics of the RCS. Then, 3 dimensional space frame members,based on the elastic beam theory, are used to model the RCS[1][2].

2) The material used for manufacturing RCS components is considered as isotropic and homogeneous state. Then, material properties defined in ASME codes[3] are directly available without any further assumption.

3) The temperature of reactor coolant is defined upon the basis of plant operation conditions and is directly applicable to the RCS metal temperature. Since the main goal of the current analysis and modeling is focused on the global behavior of the RCS during plant operation conditions, the conservatism from the assumption made here is a buffer absorbing general uncertainties such as gaps in RCS components, friction phenomena, material impurity, etc. The average coefficient of thermal expansion(CTE) is applied to each RCS component.

2.2. Modeling of RCS

GT/STRUDL[4], the commercial code widely adopted for structural analyses, was used to evaluate the thermal movement of the RCS. All RCS components were modeled into 3 dimensional beam members and actual dimensions of each component were referred to prepare the equivalent sectional properties according to the beam theory. The operation temperature and pressure of reactor coolant are shown in Table 1. Typical material properties of the RCS are listed in Table 2. Steam masses in the steam generator at the normal operation conditions were also included to evaluate the total weight of the steam generator according to the plant operation conditions. A typical RCS model using beam elements is shown on Fig. 2.

Because the general behavior of the RCS is difficult to model, much minute attention should be paid on some entries such as nozzle areas, attachments on vessel, etc., to reflect the local flexibility. To simulate the reality at junctions of vessels and nozzles, stif-

Table 1. The Operation Condition of Reactor Coolant

Item	Normal Operation	Hot Stand-by
Pressure(psig)	2250	2250
Temperature(°F)	625	565

Table 2. The Material Properties of RCS(Typical)[3]

Component	Elastic Modulus($\times 10^6$ psi)			CTE($\times 10^{-6}$)		
	500°F	600°F	700°F	500°F	600°F	700°F
RV and SG Vessel RV and SG Support RCP	25.7	25.2	24.6	7.25	7.42	7.59
Piping	27.3	26.7	25.5	6.91	7.17	7.41
RCP Support	27.0	26.4	25.3	7.70	7.83	7.94

fness matrix elements representing the local flexibility at the junctions were defined on the basis of finite element analyses[5]. Since the steam generator support structure can release the thermal expansion transferred from the hot leg by sliding itself outward from the reactor vessel, the horizontal movements were released to meet the actual boundary condition. When the steam generator sliding base moves in and outward because of the thermal movements of the reactor vessel and hot leg, a friction force is introduced at the area where the sliding base of the steam generator meets with building in terms of the static frictional coefficient. Basic ideas used for modeling the local stiffness at the steam generator inlet nozzle are shown on Fig. 3.

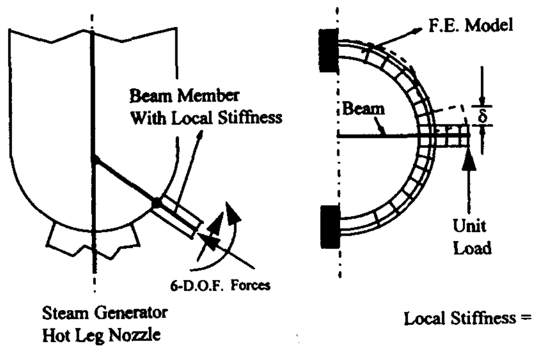


Fig. 3. Basic Concept of Local Stiffness

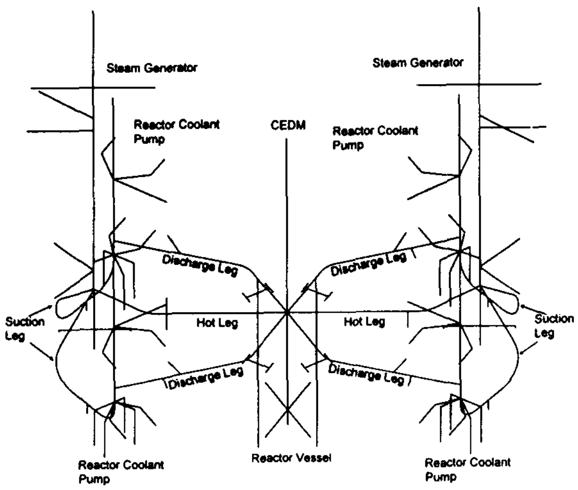


Fig. 2. Configuration of RCS Model with 3-D Beam Element

Since the insulation material surrounds each RCS component to protect the heat loss during operation, the operating temperature of most components shall be assumed to be the same as that of reactor coolant for a given condition. Then, the operating temperature of reactor coolant for a given plant condition shall be directly input for the temperature of each component. Since the insulation is not generally provided on support structures, specific thermal analyses were carried out in terms of the reactor coolant temperature and the ambient temperature. The temperature difference between hot and cold water produces local moment or corresponding rotation at the lower section of the steam generator. Detailed thermal analyses at the section including support structure were done to define an equivalent temperature which is applicable to beam members. Basic concept and thermal analysis results are shown in Fig. 4. Since the stiffness of the tubes is negligible in comparison with the

Table 3. Typical Differential Building Thermal Growth

Location	Displacement* (Typical, inches)		
	X**	Y**	Z**
RV Support Column Base	0.048	–	0.082
SG Pedestal	–	0.171	–
RCP Vertical Column Base	0.073	0.050	0.096

* Maximum Value
* Vertical datum is the bottom of RV support column base
* Horizontal datum is the RV center line
** See Fig. 1(a) for coordinate convention

steam generator, only the weight of the tube bundles was considered at modeling procedure. The weights of steam and saturated water in the steam generator were also considered according to the operation conditions.

The thermal expansion of the reactor building produces vertical and horizontal growth due to heat transfer from the RCS. These kinds of thermal effects from the building change the location of support structure and impact on the specific behavior of the RCS. But differential thermal growth of the building, which consists of concrete and steel and may not show isotropic and homogenous behavior, should be understood upon the basis of averaged displacement. Some discussions will be devoted to the issue. Table 3 shows typical values of differential building thermal growth adopted in this study.

The operation pressure of the RCS during the normal operation condition is 2250 psig. The pressure built up in the RCS produces the expansion on each component and impacts upon the global behavior of the RCS movement. Since the beam element does not permit to input pressure directly, the equivalent forces as shown in Fig. 5 are applicable.

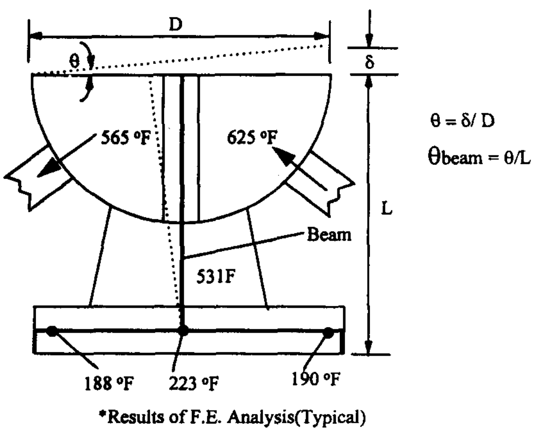


Fig. 4. Consideration of Steam Generator Lower Structure Rotation

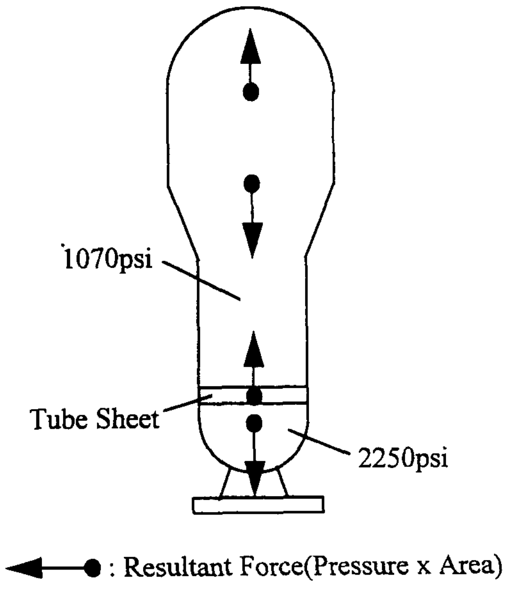


Fig. 5. Application of Pressure

Many kinds of branch lines are attached to the RCS to meet the required functions during the plant operation. Since the stiffness of RCS components is rigid in comparison with branch lines, the impact due to the thermal expansion of the branch lines is negligible.

2.4. Analyses

Total seven cases of plant loading condition were defined to analyze behaviors of the RCS. On the bases of general plant operation scenario, the cases are as follows.

1) Normal operation condition with full power.
2) Hot stand-by with 0% power.
3) Cold condition.
4) Start of plant heat-up condition.
5) End of plant heat-up condition.
6) Start of plant cool-down condition.
7) End of plant cool-down condition.

Cases of 4) through 7) could be considered as transient events during the normal operation condition. Since the gradient of the plant temperature during heat-up and cool-down process, herein assumed as a rate of 100°F per hour, is not generally steep, those transients could be considered as a quasi-static condition. Then, the only start or final condition is considered to evaluate the results. The static frictional coefficient of 0.3 was considered, for the cases of 4) through 7), at the bottom of steam generator sliding base members to resist the thermal expansion. Analyses were done on VAX/VMS 6320 using GT-STRUDL version 9101.

3. Measurement of RCS Thermal Movement

Many locations and items were selected to find out the general behavior of the thermal expansion of the RCS during heat-up and cool-down process. The amount of critical gaps and displacements affecting on the system integrity were measured closely according to consequential temperature plateau. Total 7 measured items at 3 locations were selected to probe the specific behavior of the RCS and shown in Fig. 6 through Fig. 8. The test results at the reactor coolant temperature of 565°F, including both heat-up and cool-down cases, were referred to prove the validity of the current analyses. Fig. 6 through Fig. 8 show brief configurations of the measured items and corresponding locations for the verification procedure. The results of computer analyses with the loading condition of case 2 discussed in section 2. 4 will be used for the verification procedure.

Item G1 through G4 represent the variation of distance between the key and the key way at the steam generator lower support structure. Because the hot leg piping pushes off the steam generator due to the thermal expansion, G1 through G4 at a given temperature plateau represent an actual thermal expansion occurring at the steam generator lower support structure. Item H1 and H2, as shown in Fig. 7, represent the vertical movement of center line of steam generator upper keys. Item S represents the variation of RCP snubber stroke. As the temperature of the RCS increases, the length of item S will decrease. The item S is one of the most important indicators to verify the thermal behavior of the RCP.

The accuracy of measured data may depend on the accuracy of measuring tools or instruments. Other disturbance may come from simultaneous movements of the building, structure and measuring instruments during heat-up or cool-down process. Since the dimensions of the relating instruments are relatively small in comparison with those of the RCS, then imaginable errors could be discarded in the assessment procedure. Detail discussions on measured data will be devoted on the following section.

4. Results and Discussions

Table 4 shows the impact of differential building thermal growth on the global thermal behavior of the RCS. Two analyses results are very close each other as shown in the tables. At the SG upper key location, maximum 16% of discrepancy was estimated as shown in Table 4-A. The main source of these deviations can be depicted in terms of the rotation of the steam generator due to the vertical movement of the steam generator building structure. The building

Table 4-A. Displacement at SG Upper Key Location With/Without Building Thermal Growth (at H1 Location in Fig. 7)

Case	Dir. **	Without Building Thermal Growth	With Building Thermal Growth	Deviation*(%)
Normal Operation	X	−2.20	−1.94	13.4
	Y	2.28	2.50	9.6
	Z	0.00	0.00	0.0
Hot Stand-by	X	−1.88	−1.62	16.0
	Y	2.29	2.50	9.2
	Z	0.00	0.00	0.0

* Maximum Rate Unit)inches

** See Fig. 1(a) for coordinate convention

Table 4-B. Displacement of SG Center at Lower Key Elevation With/Without Building Thermal Growth

Case	Dir. **	Without Building Thermal Growth	With Building Thermal Growth	Deviation*(%)
Normal Operation	X	−1.50	−1.51	0.6
	Y	0.00	0.17***	−
	Z	0.00	0.00	0.0
Hot Stand-by	X	−1.37	−1.38	0.7
	Y	2.29	0.17***	−
	Z	0.00	0.00	0.0

* Maximum Rate Unit) inches

** See Fig. 1(a) for coordinate convention

*** See Table 3

Table 4-C. Displacement at RCP Snubber Location With/Without Building Thermal Growth

Case	Dir. **	Without Building Thermal Growth	With Building Thermal Growth	Deviation*(%)
Normal Operation	X	−1.21	−1.17	3.4
	Y	0.53	0.56	6.3
	Z	0.70	0.71	2.9
Hot Stand-by	X	−1.22	−1.62	3.4
	Y	0.53	0.57	5.8
	Z	0.70	0.71	4.3

* Maximum Rate Unit) inches

** See Fig. 1(a) for coordinate convention growth at the steam generator lower support makes the angle of the steam generator vertical center line decrease slightly. Since the elevation of the upper keys is very high, magnified horizontal movement due to the steam generator rotation creates a relatively large deviation. However, a relatively small deviation is found at the steam generator lower support structure and at the RCP area as shown in Table 4-B and 4-C. Though the results without the differential building thermal growth still show an acceptable deviation, the impact of differential building thermal growth should be closely monitored throughout analysis.

Table 5 through 7 show the comparison of test and analyses results at given locations as shown in Fig. 6 through Fig. 8. The analyses data were supplied with the differential building thermal growth at hot stand-by condition of 565°F. The measurement was carried out at two conditions with the same temperature of 565°F. Test #1 was performed at the end of heat-up process and Test #2 data were picked up at the start of cool-down process.

Table 5 shows the horizontal displacement of the steam generator center at the lower key elevation. Item G1 through G4 represent the relative displacements of the steam generator sliding base. The average numbers, which mean the displacements at the center of the steam generator, are close to analysis results.

Table 5. Results at Steam Generator Center (Horizontal Displacement)

SG No.	Test #1	Test #2	Analysis	Deviation*(%)
1	1.44	1.44	1.38	4.3
2	1.44	1.42	1.38	4.3

* Maximum Rate

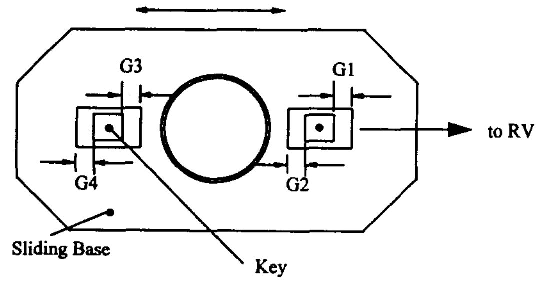


Fig. 6. Steam Generator Base Plate

Table 6-A and 6-B show the vertical displacement of the steam generator at the upper key location. Though the elevations of upper keys are rather high, the results generally showed good agreement. The difference of the measured data between SG #1 and SG #2 test results may come from numerous well-known or uncertain sources, but results are still acceptable. The temperature of 565°F lasted for hours before performing Test #2, whereas Test #1 was tried at the moment the target temperature of 565°F achieved. Then, Test #1 may tend to show an instantaneous thermal expansion but the order of deviations falls within an acceptable range. The typical differential building thermal growth value used for the analysis is 0.17" at the steam generator sliding base elevation; see Table 3. The direct impact of the differential building thermal growth is readable by comparing the vertical movement at the steam generator upper key location(Table 4-B). Since the deviation between the analysis and measured data is very small as shown in Table 6-A and 6-B, it is believed that the current differential building thermal growth value is reasonable. Each plant may have a specific amount of the differential building thermal growth but the impact of the building itself is one of the non-critical parameters in comparison with the thermal behavior of RCS components.

Table 7 shows typical results of test and analysis for item S representing the total length of the reactor coolant pump snubber strokes. Since the pump support structure have pin-jointed structures to allow motion in horizontal plane, the thermal expansion of the RCS pushes the pump structure out by way of the discharge leg. Table 7 shows an acceptable deviation for the current test. The main sources of that deviation may come from even minor difference of

Table 6-A. Results at Steam Generator #1 Upper Keys (Vertical Displacement)

	Test #1	Test #2	Analysis	Deviation*(%)
H1**	2.42	2.32	2.50	7.7
H2**	2.44	2.36	2.44	3.4

* Maximum Rate unit) inches

** Relative Displacement

Table 6-B. Results at Steam Generator #2 Upper Keys (Vertical Displacement)

	Test #1	Test #2	Analysis	Deviation*(%)
H1**	2.36	2.32	2.50	7.7
H2**	2.38	2.32	2.44	5.2

* Maximum Rate unit) inches

** Relative Displacement

Table 7. Results at Reactor Coolant Pump Snubber

RCP No.	Test #1	Test #2	Analysis	Deviation*(%)
1A	1.44	1.39	1.39	3.6
1B	1.41	1.38	1.39	1.5
2A	1.30	1.28	1.39	8.6
2B	1.38	1.35	1.39	2.2

* Maximum Rate unit) inches

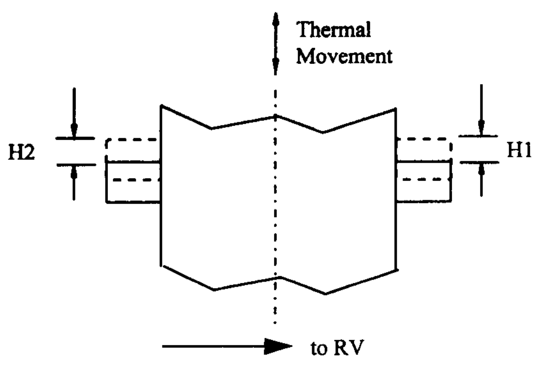


Fig. 7. Steam Generator Upper Keys

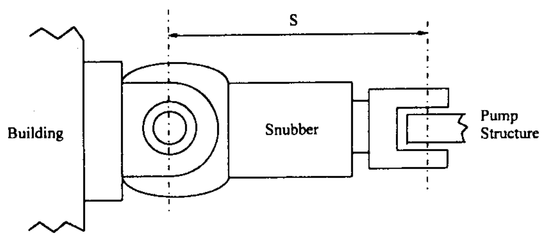


Fig. 8. RCP Snubber Stroke

analysis model and actual installation of RCS structure during construction and other well-known sources.

It is believed that the current RCS analysis presented in this paper is properly performed on the basis of discussions made here. The former assumption that the temperature of RCS components is the same as that of reactor coolant is also proved to be applicable throughout discussions. Though the actual metal temperature of RCS component is lower than the fluid temperature, that impact is not so remarkable with respect to the global RCS thermal movement. The test results obtained from the heat-up condition showed a little tendency of instantaneous thermal expansion but the discrepancy falls within an acceptable range. Thus the application of average CTE values is acceptable. Other items discussed in modeling of the RCS are also proved to be appropriate on the basis of test results.

5. Conclusion

The RCS thermal analysis results presented in this study show good agreement with test ones within a range of around 10% difference. The impacts of the differential building thermal growth on the global RCS thermal movement are negligible but specific attention throughout the analysis should be paid to monitor the expectable conservatism. The assumption of RCS component temperature and application of average CTE value is proved to be acceptable.

The other discrepancies extracted by discussion could be wrap up in an expectable conservatism that shall be included in a basic design margin.

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