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Nozzle Dam Design Improvement in Steam Generator

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증기발생기용 노즐댐 설계개선

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Abstract

The normal shutdown and maintenance period of a nuclear power plant can be remarkably shortened when the examination and maintenance works in steam generator tubes are simultaneously carried out with refueling job. There are nozzle dams to block the coolant flow from reactor to steam generator. Workers are reluctant to install nozzle dam because of the high radiation exposure and the limited working space in steam generator. Moreover, the heavy weight of present nozzle dam makes its installation and removal works much difficult.

In this paper, a lighter KAERI nozzle dam with increased flexural rigidity-to-weight was designed and manufactured by changing the structure design of the present nozzle dam and by selecting new material, carbon fiber-reinforced plastic.

요 약

원자로의 가동중지 중이나·재장전시 증기발생기의 세관검사 및 보수작업을 병행하면 원전의 운전정지 보수기간을 현저하게 단축할 수 있다. 이때 원자로가 설치되어 있는 수조의 냉각수가 증기발생기내로 유입되는 것을 막는 장비로써 노즐댐이 있다. 노즐댐의 설치는 고방사선환경과 제한된 공간에서 작업을 해야 하는 특수성 때문에 작업자들이 기피하는 현상을 보인다. 현재 쓰이고 있는 무거운 노즐댐은 노즐댐 설치 및 제거작업에 장애가 되는 가장 큰 요인이다. 본 논문에서는 노즐댐의 재질선정과 구조설계를 병행하여 현재 쓰이고 있는 노즐댐보다 가벼우면서도 굽힘강성 대 무게비와 비강도가 증가된 노즐댐을 설계하였으며, 탄소섬유강화 복합재료로 경량노즐댐을 제작 완료하였다.

1. Introduction

Nozzle dam is a special closure to block the coolant flow from reactor at the inlet/outlet nozzles in steam generator, and it is usually installed manually. The manual installation of nozzle dam induces radiation exposure to the working personnel. Since the exposure dosage during its installation and removal becomes sometimes more than 15% of the whole radiation exposures absorbed in nuclear plant, the workers are reluctant to do the related works[1]. In order to protect the workers from the radiation exposure, a new design concept of nozzle dam should be developed such as light weight nozzle dam which can be installed in a shorter time or installed by a robot.

Three kinds of nozzle dam are used in Korea, designed by Westinghouse, CE(Combustion Engineering) and NES(Nuclear Energy Service). Westinghouse type is used in KORI nuclear power plant. CE and NES types are to be installed in Yonggwang 3&4 and Ulchin 3&4, respectively in near future.

Westinghouse type nozzle dam is so heavy that workers have much difficulty in doing nozzle dam installation/removal. It takes at least 30 minutes to install one nozzle dam by tightly fastening 20 bolts to provide both structural stability and sealing performance. Trundle[2, 3] has improved the installation technique by devising a new transporting system of the heavy nozzle dam.

CE type nozzle dam for Yonggwang 3&4 is composed of one set of wet and dry dams, so called double nozzle dam, and sealing mechanism. The dams are installed by inserting pins into the holes on nozzle wall of steam generator. They had been improved continously until Weisel[4] devised a single nozzle dam. McDonald[5] invented an instrument, with which workers could install nozzle dam without jumpers into steam generator's bowl.

NES type nozzle dam for Ulchin 3&4 is conceptually similar to CE's single nozzle dam. Disk of the nozzle dam is divided into three pieces for one center and two side sections to easily transport them through the small manway opening of steam generator. It is installed by inserting pins into the holes on a retention ring already welded on steam generator nozzle. The whole installation time of this nozzle dam takes only a few minutes.

Another type of nozzle dam, not in use in Korea, is produced by BRAND Utilities, Inc. USA. Disk of the nozzle dam is also divided into three pieces. The surface of the disk is machined with a contour corresponding to the bending moment curve over the disk[6]. A separate sealing mechanism is used to reduce the number of bolts to be fastened. It takes only a few minutes to install BRAND nozzle dam. With handling lugs attached, the BRAND nozzle dam can be remotely installed by a robot[7]. After it was verified with ROMA(Remotely Operated Manipulator Arm) robot of BRAND at Catawba in USA, 1990, it not only applied to other nuclear power plants but also verified with ROSA III(Remotely Operated Service Arm) of Westinghouse at Farley in 1992.

Since no research on design technology and remote control of nozzle dam has been performed yet in Koera, it is necessary to develop nozzle dam system technology. The optimally designed nozzle dam and improved robot technology can reduce dependence of foreign technology and contribute to automation technology in domestic industry.

2. Characteristics of Nozzle Dam.

Nozzle dam can be generally characterized by various parameters, such as size, sealing performance, flexural rigidity-to-weight, strength, etc.

The size of nozzle dam is determined by the diameter of nozzle ring(called retention ring sometimes) welded on steam generator. The size of KORI nozzle dam with Westinghouse type is 40"(1.016 m) in diameter, while the CE type nozzle dams are 30"(0.762 m) and 42"(1.066 m) in diameters for inlet and outlet nozzle, respectively.

It is hard to define the sealing performance quantitatively, however, no leakage is generally required as the acceptance criteria.

Both weight and stiffness of nozzle dam are so important that a parameter(flexural rigidity-to-weight ratio) can be defined for the structural design of nozzle dam. The flexural rigidity to explain a structural stiffness can be defined as the product of the elastic modulus for the selected material and the moment of inertia for the structural design.

In this study, the flexural rigidity-to-weight ratio is selected as a design parameter to determine the structural optimum design of nozzle dam. Table 1 shows the weight and material of nozzle dams investigated. The center section of KORI nozzle dam weighs about 34kg, while the center sections of BRAND and NES nozzle dam weigh 27kg and 15kg, respectively. Table 2 shows the flexural rigidity-to-weight ratio obtained for nozzle dams investigated. The flexural rigidity-to-weight ratio for the center section of KORI nozzle dam (18.25×10^3 Nm^2/kg) is lower than that of NES center section (25.07×10^3 Nm^2/kg). This implies that the flexural rigidity-to-weight ratio of KORI can be raised through design improvement.

Both BRAND and NES nozzle dams were made of Al 2024-T351, of which yield strength and tensile strength are 290 MPa and 420 MPa, respectively. KORI nozzle dam was made of Al 5052-H32, of which yield strength and tensile strength are 160 MPa and 215 MPa, respectively. The material

Table 1. Weights and Materials of Nozzle Dams Investigated

Nozzle Dam Type		Nozzle Dam Weight		Material
		Center Section	Side Section	
KORI 2 Nozzle Dam		34.02 Kg	34.02 Kg (folding cover)	Aluminum Alloy 5052-H32
BRAND Nozzle Dam		27.21 kg	15.88 kg	Aluminum Alloy 2024-T351
NES Nozzle Dam (Type C-2)	30″ (0.762 m)	14.97 kg	–	Aluminum Alloy 2024-T351
	42″ (1.066 m)	15.42 kg	–	Aluminum Alloy 2024-T351

Table 2. Flexural Rigidity-to-Weight Ratio of Nozzle Dam

Nozzle Type		Weight	Young's Modulus(E)	Moment of Inertia : Ic	Flexural Rigidity-to-Weight Ratio $\times10^3$
KORI Nozzle Dam (Center Section)		34.02 kg	69.3 GPa	8.9608×10^{-6} (m^4)	18.25 ($N\ m^2/kg$)
NES Nozzle Dam (Type C-2)	30″ center (0.762 m)	14.97 kg	73.14 GPa	5.1329×10^{-6} (m^4)	25.07 ($N\ m^2/kg$)
	42″ center (1.066 m)	15.42 kg	73.14 GPa	5.4942×10^{-6} (m^4)	26.23 ($N\ m^2/kg$)
	42″ middle (1.066 m)	22.68 kg	73.14 GPa	7.4505×10^{-6} (m^4)	23.97 ($N\ m^2/kg$)
KAERI Nozzle Dam Center Section		10.6 kg	63.5 GPa	4.9800×10^{-6} (m^4)	29.83 ($N\ m^2/kg$)

$$\text{Flexural Rigidity-to-Weight Ratio} = \frac{E\,I}{\text{Weight}}$$

strength of KORI one is the lowest value among them.

3. Conceptual Design of KAERI Nozzle Dam

3.1. Construction Code

Since there are no specific construction codes for nozzle dam of steam generator, ASME Code Section Ⅲ[8] is selected for the construction guide in the nozzle dam design because the code is recommended in general as design guide for nuclear components and structures.

Table 3 represents the design criteria applied to KAERI nozzle dam structural design.

3.2. Material Selection of Nozzle Dam

For the design of light weight nozzle dam with high strength, material with both high specific modulus(E/r) and high specific strength(S/r) must be used, where E, S, and r stand for the elastic modulus, tensile strength, and specific gravity of the material, respectively.

Table 3. Design Stress Criteria of Nozzle Dam

Loading Condition	Stress Type	Application	Allowable Stress
Design	P_m	Plate	$S_m = (1/4)\,\sigma_u$
Condition	$P_L + P_b$	Plate	$(1.5)S_m = (1/4)(1.5)\,\sigma_u$
Normal Operating Condition	$P_L + P_b + P_e + Q$	Juntion of rib, side wall, and flange	$(3)Sm = (3)(1/4)\,\sigma_u$

P_m : Primary Membrane, P_L : Primary Local Membrane
P_b : Primary Bending
P_e : Secondary Thermal Expansion
Q : Secondary Membrane plus Bending

Table 4. Specific Modulus and Strength for Various Materials

Material	Ultimate Tensile Strength (GPa)	Elastic Modulus (GPa)	Specific Strength (GPa)	Specific Modulus (GPa)
Composite Material				
A-epoxy	1.5	110	1.00	74
HT-epoxy	1.9	130	1.27	87
HM-epoxy	1.5	190	0.94	119
HPW193/RS1222*	0.76	64	0.49	41
E glass-epoxy	1.0	42	0.50	21
Aramid-epoxy	1.8	77	1.30	56
Steel	1.0	210	0.13	27
Titanium	1.27	117	0.27	25
Aluminum 2024	0.48	69	0.17	24

A : General purpose, HT : High strength
HM : High modulus
* Carbon Fiber-Reinforced composite materials supplied by Hankuk Fiber Inc.

In general, the specific moduli of metallic materials are known to be almost the same, while those of composite materials vary widely as shown in Table 4. The specific moduli of composite materials are generally found to be higher than those of metallic materials. This implies that the flexural rigidity-to-weight ratio can be improved if composite material instead of metallic material is used for nozzle dam.

Carbon fiber-reinforced plastic is selected for the KAERI nozzle dam structural material. Because of its high specific modulus and specific strength, fiber-reinforced composite materials are often used for airplane and automobile requiring light material with good fatigue characteristics[9]. By the same reasons, fiber-reinforced composite material is selected as the most suitable material for the high strength but light weight KAERI nozzle dam.

3.3. Structural Design of KAERI Nozzle Dam

The structural design requirements of KAERI nozzle dam are as follows;

(1) KAERI nozzle dam should be designed so as to be installed in KORI steam generator.
(2) KAERI nozzle dam should be not only remotely operated by a robot but also operated manually.
(3) KAERI nozzle dam should have higher flexural rigidity-to-weight ratio than that of the present nozzle dams.

Figure 1 shows the KAERI nozzle dam designed according to the above design requirements. Its size and the fastening method with nozzle ring are the same as those of KORI nozzle dam. The handles (item #5 in Fig. 1) are for robot and manual operations. The flexural rigidity-to-weight ratio KAERI nozzle dam is higher than that of NES nozzle dam as shown in Table 2.

3.4. Manufacture of Nozzle Dam

Composite materials are usually manufactured to a final product by molding process. In this process, the composite material should be prepared in a shape of prepregs which are the preimpregnated sheet of fiber and epoxy resin. Epoxy resin is a kind of thermosetting resin, which has proper mechanical and chemical characteristics as matrix.

Among the several molding process, autoclave/vacuum bag degassing method was used to fabricate KAERI nozzle dam. For the thickness of 12 mm, 57 prepregs were laminated and cured on a metallic die machined in the form of KAERI nozzle dam.

4. Evaluation of Structural Integrity

4.1. FEM Model of KAERI Nozzle Dam

Althougth the high strength material is selected for KAERI nozzle dam, the strutural integrity should be evaluated through the stress analysis.

The stresses occurred by the pressure acting on nozzle dam were analyzed using the finite element method(FEM) via ANSYS code. The calculated stress intensities were compared with the allowable stress intensities given in Table 3.

FE model of KAERI nozzle dam was shown in Figure 2. A shell element (SHELL 93 in ANSYS) was used for FE model consisted of plate, rib, side wall and flange.

Due to the symmetry of nozzle dam structure, only 1/4 portion was modeled to have 3223 nodes and 1062 elements. All degrees of freedom at the bolted positions in the flange were assumed to be fixed, and the tangential directions at both $\theta=0°$ and $\theta=90°$ were also constrained due to the symmetry.

4.2. Material Properties

Material properties of the CFRP used are as follows(provided by Hankuk Fiber Inc.):

Young's modulus: 63.5 GPa
Tensile strength : 765 MPa
Poisson's ratio : 0.086

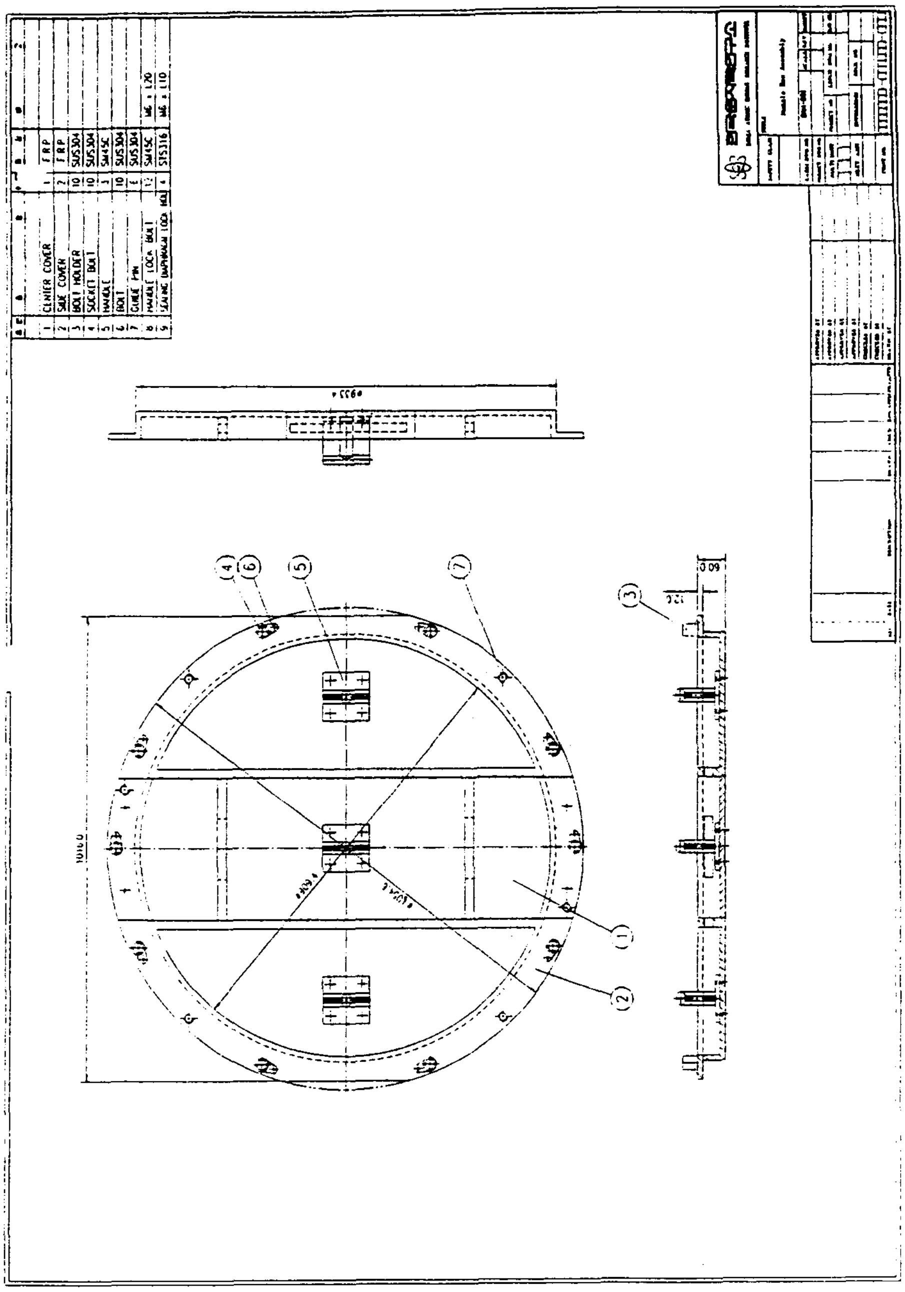

Fig. 1. KAERI Nozzle Dam

Density: 1543 Kg/m^3

4.3. Stress Analysis Results.

Stresses of KAERI nozzle dam were calculated under both design condition and normal operating condition because the stress types considered in two conditions are different each other as shown in Table 3.

The maximum stresses under the design condition

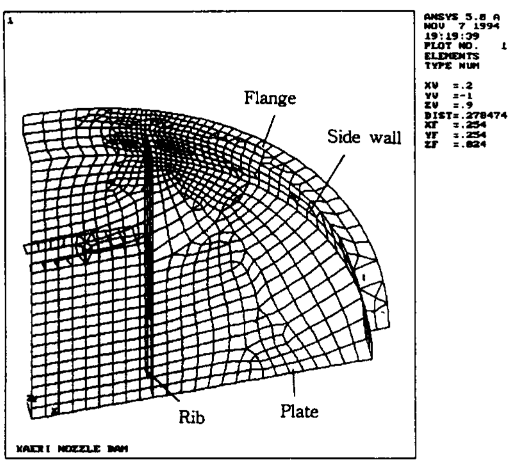

Fig. 2. Finite Element Model of KAERI Nozzle Dam

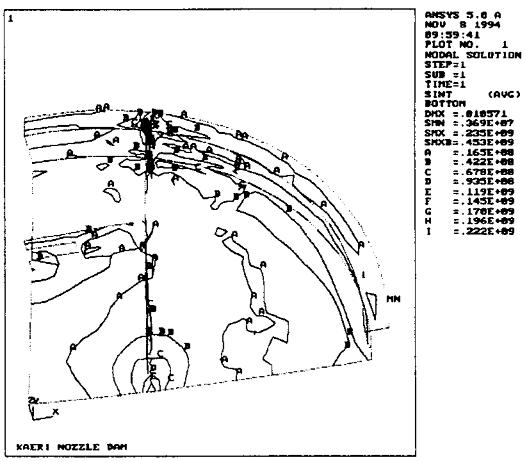

Fig. 4. Stress Intensity Contours of KAERI Nozzle Dam Uunder Normal Operation Condition

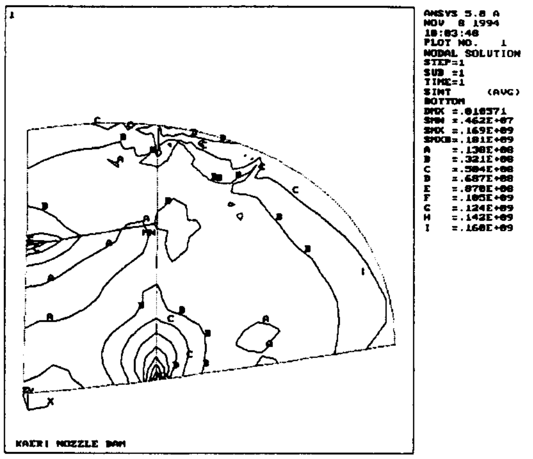

Fig. 3. Stress Intensity Contours at Plate under Design Load

were in Table 5 and compared with the allowable stresses computed from the criteria in Table 3. Figure 3 represents the stress intensity contour in the nozzle dam plate. The maximum primary membrane stress occurred at the junction of plate and rib as shown in Fig. 3 was lower than the allowable stress. Maximum primary membrane plus bending stress was also lower than the allowable.

The stress analysis results under the normal operating condition were summarized in Table 6 and the stress contour is shown in Figure 4. The maximum stress including the local membrane stress and secondary stress is occurred at the junction of rib, side wall and flange of the nozzle dam. As shown in Table 6, the maximum stresses under the normal operating condition were also lower than the allowables.

To sum up the results, the maximum stresses at the plate and the conjunction of rib, side wall and flange in KAERI nozzle dam were lower than the allowables given by ASME Code criteria. It can be therefore concluded that the structural integrity of the KAERI nozzle dam is maintained.

To consider the dynamic behavior of KAERI nozzle dam in seismic event, the fundamental natural frequency of the nozzle dam was calculated. The computed natural frequency was 168Hz, which is much higher than 30Hz, the usual zero period frequency in seismic design. Therefore it can be said that the KAERI nozzle dam can be treated as a rigid component in seismic event.

Table 5. Nozzle Dam Stresses under Design Condition

Condition	Design Loading = 110 KPa(16 Psi)			
Component	Location	Type	Stress	Allowable
Plate	Junction of	P_m	152 MPa	191 MPa
	Plate and Rib	$P_L + P_b$	187 MPa	286 MPa

P_m : Primary General Membrane
P_L : Primary Local Membrane
P_b : Primary Bending

Table 6. Nozzle Dam Stresses under Normal Operating Condition

Condition	Normal Operation Loading = 89.7 KPa(13 Psi)			
Component	Location	Type	Stress	Allowable
Rib	Junction of rib, side wall, and flange	$P_L+P_b+P_e+Q$	348 MPa	573 MPa
Side Wall	Junction of rib, side wall, and flange	$P_L+P_b+P_e+Q$	429 MPa	573 MPa
Flange	Junction of rib, side wall, and flange	$P_L+P_b+P_e+Q$	507 MPa	573 MPa

P_L : Primary Local Membrane
P_b : Primary Bending
P_e : Secondary Thermal Expansion
Q : Secondary Membrane plus Bending

5. Conclusion

A new nozzle dam(KAERI nozzle dam) for KORI steam generator is designed for a robot operation as well as manual operation. The flexural rigidity-to-weight ratio and specific strength are improved by using carbon fiber reinforced composite material. The stress design criteria for the structural integrity given in ASME Code are satisfied througth the stress analysis. It is also known that the nozzle dam can be treated as a rigid component in seismic event.

The KAERI nozzle dam will be installed and tested in KORI plant when the sealing mechanism is manufactured.

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