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EFFECTIVENESS OF THE HIGH CAPACITY BLOWDOWN FOR STEAM GENERATOR SLUDGE REMOVAL

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The steam generator blowdown system is designed to remove the impurities to prevent the steam generator from degradation by the accumulation and buildup of corrosion products. Two-dimensional transient analysis has been performed to simulate the accumulation process of the impurities on the steam generator tubesheet and to investigate the effectiveness of the blowdown on removing the solid particles of various sizes. The solid-water two phase flow has been analyzed with the computational fluid dynamic code, FLUENT. The results show the development of the accumulation and the amount of the sludge on the tubesheet with respect to particle size and blowdown flowrate. The high capacity blowdown is estimated as an effective method for removing the bigger particles. The data from this study will provide useful information for the design and operation of the high capacity blowdown system.

1. INTRODUCTION

The steam generator(SG) of the Korea Standard Nuclear Plant (KSNP) is an inverted U-tube type recirculating unit with an integral economizer and two blowdown lines whose flow capacity is as high as 10% maximum steaming rate (MSR)[1]. As shown in Figure 1, the economizer is a semi-cylindrical section of the tube bundle above the tubesheet on the cold leg side. A vertical divider plate separates the economizer from the adjacent hot side evaporator region. Feedwater is introduced into the economizer region and heated to near saturation conditions before joining the cold side downcomer water and fluid from the hot side evaporator.

One of the primary causes of SG degradation, which may eventually lead to tube plugging, is the accumulation and buildup of corrosion products transported to the SG[2]. Impurities and corrosion products enter the SG through the feedwater system and these contaminants produce sludge, which can deposit in crevices, on tube surfaces and on the tubesheet. Aggressive impurities from the condenser cooling water leakage may cause serious damage to the SG. Soluble impurities can also concentrate as a result of the boiling process with a potential for tube degradation.

The SG bottom blowdown system provides a capability to adequately blow down the SG under hot operating conditions to minimize the buildup of sludge on the tubesheet, to control the chemistry condition and to reduce the concentration of impurities in the recirculating flow. On-line corrosion product removal is accomplished by blowdown of the bulk secondary fluid through the blowdown ducts located at the center of the tubesheet (see Figure 1). Continuous normal blowdown rate is maintained between 0.2 and 1% MSR.

The operating experiences[3] show that, with the normal blowdown rate less than 1% MSR, the particles whose sizes vary between 0.6 and 8 ㎛ can be removed. Fluid removed from the hot side of the tube bundle by the continuous normal blowdown contains recirculated liquid that has been concentrated in soluble corrosion products by boiling and insoluble corrosion products. Studies[3] have shown that incoming particle sizes from feedwater are 1 to 3 ㎛. As parts of these particles reside in the recirculating flow without being removed by the normal bottom blowdown system, they agglomerate and reach the sizes of 8 to 24 ㎛ or larger. Therefore, a higher blowdown flow rate may be required to remove agglomerated particles in order to prevent sticking them to the tubesheet surface.

It is difficult for the designer to determine a blowdown flowrate that is to effectively remove sludge piled on the tubesheet because of the unknown kinds and sizes of the particles. Conventionally, the high capacity blowdown flow rate has been determined based on the maximum capability that the system could provide without causing significant operating transient, i.e., SG level transient. In KSNP, the high capacity blowdown system is designed to provide a blowdown flowrate of about 10% MSR. The objective of the high capacity blowdown is to periodically increase the blowdown flowrate to increase the flow velocity and to enhance the sweeping of deposited sludge from the tubesheet. However, the operation of high capacity blowdown system is so complicated and requires so many precautionary actions to be taken by the plant operators.

Since the high capacity blowdown capability of removing sludge piled on the tubesheet in terms of sludge size is not well understood, the unknown capability of the system makes it difficult to determine the effectiveness of the system. Therefore, the relationship between the blowdown flowrate and the removable particle size will be useful information for the main steam and feedwater systems designers as well as the plant operators. The objective of this study is to predict the effectiveness of the SG blowdown to the removal of the sludge by analyzing the behavior of the iron-oxide (Fe_3O_4, specific gravity 5.2) particles of various sizes with the aid of the computational method.

2. ANALYSIS

2.1 Analysis Model and Governing Equations

Figure 1 shows the SG lower part and the blowdown system near the tubesheet. The blowdown system consists of a separate collection duct and nozzle for both hot and cold sides separated by the economizer divider plate. Each leg of the system is made up of a 3x6 inch hook shaped duct located on the secondary side of the tubesheet below the divider plate. On each side, suction is taken through holes in a section of duct which extends 180 degrees around the support cylinder at the center of the tube bundle and exits through a 3 inch drilled passageway in the tubesheet and 6 inch blowdown nozzle.

The analysis model using the axisymmetric condition is shown in Figure 2, which represents the lower part of the SG near the tubesheet. The grid of 85x73 (radial x axial) is employed after the adequacy of the grid has been reviewed (Figure 3). The analysis model includes two side walls, the bottom of the tube sheet, one inlet and two outlets: one inlet from the downcomer, one outlet to the upper evaporating region and the other outlet at the bottom to the blowdown system.

The velocity of 7.17 m/s with a uniform velocity profile is given at the inlet. The inlet velocity is adjusted to compensate for the tube volume which is modeled by porous media assumption. The inlet width is 0.03 m.

The outlet 1 is a main exit where the Neumann boundary condition is specified for the dependent variables. The blowdown flow rate is given as a boundary condition at the outlet 2, and varies from 0% to 20% MSR (9.0m/s). The blowdown holes of 0.035 m diameter are modeled as 0.01 m wide slit. Also, the saturated water at 289 °C is assumed even though the water is heated up and begin to evaporate near the outlet 1.

The governing equations for the 2-dimensional axisymmetric unsteady state include the conservation of mass and momentum of the water and the particles. Time increment is set at 0.01 seconds. In the momentum equation, the tube bundle is modeled as a porous medium. The k-ε turbulence model has been used in the analysis. The analysis has been performed with the computational fluid dynamics code, FLUENT with SIMPLE algorithm[4].

2.2 Porous medium model

The flow region which has the bundle of tubes of 3/4 inch diameter and 1 inch pitch is modeled by the porous media. The porous media model is nothing more than an added momentum sink in the governing momentum equation.

Momentum equations are solved in the porous medium, augmented by a general momentum sink:

$$\frac{\mu}{\beta} V + C_2\left(\frac{1}{2}\rho V\,|V|\right)$$

where β and C_2 are empirical parameters of the permeability in each component direction and the inertial resistance factor, respectively. In laminar flows through porous media, the pressure drop is typically proportional to velocity and C_2 is zero. At high flow velocities, the constant C_2 provides a correction for inertial losses in the porous medium.

In this analysis eliminating the permeability term and using the inertial loss term alone yield a simplified form of the porous media equation with C_{2i} of 20 and C_{2j} of 8.6 which are obtained to get a similar pressure and velocity distribution to the ATHOS calculation[3]. ATHOS (Analysis of the Thermal-Hydraulics Of Steam Generators) is a three-dimensional, two-phase, steady state and transient code for thermal-hydraulic analysis of recirculating U-tube SG.

2.3 Fluid-solid multiphase model

After a steady state solution of a single phase of water is obtained, the water-solid multiphase model is introduced with additional sets of conservation equations. The multiphase flow is described with the concept of phasic volume fractions which represent the space occupied by each phase. The law of conservation of mass and momentum is satisfied by each phase individually. The volume fraction of each phase is calculated from a continuity equation. In this analysis the flow behavior of a water-solid mixture is described.

The FLUENT code uses the fluid-solid exchange coefficient derived by Syamlal and O'brian [4,5] with correlations between the terminal velocities of particles, volume fraction and relative Reylonds number. Drag coefficient derived by Dalla Valle [6] is used. The fluid-solid exchange coefficient K_{sf} in the momentum equations for the fluid and solid has the form

$$K_{sf} = \frac{3\alpha_s\,\alpha_f\,\rho_f}{4v_{rs}^2\,d_s}\,C_D\!\left(\frac{Re_s}{v_{rs}}\right)|\,\overline{u_s} - \overline{u_f}\,|$$

where α is the volume fraction, v_{rs} is the terminal velocity, d is the solid diameter, C_d is the drag coefficient, Re_s is the relative Reynolds number based on the relative velocity, u is velocity, and the subscript f and s are for the fluid and solid phase, respectively.

The analyses have been performed for the particle sizes of 1㎛, 10㎛, 30㎛ and 50㎛. Once the steady state flow field of water is obtained, the particles of each size are injected with water through the inlet 1. To accelerate the accumulation process the volume fraction of the particle at inlet is assumed 10%.

3. RESULTS AND DISCUSSIONS

3.1 Results

Figure 4 shows the stream line with 10% MSR blowdown at t=10 s. A small recirculating flow near the inlet is found and the stream line to the blowdown exit is also depicted. In the upper region beyond z=0.8m, the radial velocity is nearly zero and the water flows in parallel with the z-axis. With 0 % MSR blowdown, a small recirculating zone near the blowdown exit exists and the sludge can be accumulated in this region.

Figure 5 shows the concentration distribution of the various particle sizes at t=10s with the normal blowdown flowrate of 1% MSR. The particles of 1㎛ flow with water and do not accumulate much at the bottom. The bigger the particles become, the more the particles accumulate on the bottom of the tube sheet. Since the particles larger than 50 ㎛ are hardly able to flow with water near the tubesheet, the blowdown may not be very effective for the removal of such particles.

Figure 6 represents the accumulation development of the particles of 50 ㎛ with the blowdown flowrate of 10 % MSR. The particles get to the blowdown exit at about 2.3 seconds, and the accumulated sludge increases with time.

Figure 7 shows the accumulation of the particles of 10 ㎛ with various blowdown flowrates. As the blowdown flowrate increases, the amount of the accumulated sludge decreases. The normal blowdown flowrate of 1% MSR (Figure 5 b) is shown to be insufficient for the removal of 10 ㎛ particles. Therefore, the high capacity blowdown is necessary for the sludge removal of greater than 10㎛ particles which are not likely to be removed by the normal blowdown.

Figure 8 shows the radial velocity distributions at z= 0.01 m near the tubesheet with various blowdown flowrates. The radial velocity decreases gradually and increases again as it approaches the blowdown exit. The location of the minimum velocity moves outward as the blowdown flowrate increases. Since the sludge is likely to accumulate at the area where the velocity is small, the inner portion of the tube bundle, 0.3-0.4 m away from the blowdown exit, is expected to be the place where sludge accumulations are the heaviest. The velocity near the blowdown exit increases with the increase of the blowdown flowrate, but the blowdown flowrate has an effect on the radial velocity distribution within about 0.5 m from the blowdown exit. The velocity distribution beyond this region is not affected by the blowdown flowrate. The ATHOS data[3] on the figure is the radial velocity at the higher elevation of z=0.1m which is the first node from the bottom of the SG, and due to the limited grid size the local velocity near the bottom can not be well described with ATHOS code. The difference may come from the evaporation which accelerates the fluid.

Figure 9 represents the sludge mass of various sizes of particles accumulated on the tubesheet with respect to the blowdown flowrate. The maximum volume fraction for the solid phase is limited to a value of 0.6 for mono dispersed spheres in the calculation. The control volume whose particle volume fraction is larger than 0.5 is assumed to have the accumulated sludge with its concentration. Since the small particles up to 10㎛ easily flow with water, only small amount of sludge accumulates on the tubesheet regardless of the blowdown flowrate. The accumulation of the bigger particles of 30㎛ and 50㎛ is large and reduces with the increase of the blowdown flowrate resulting in, for example, 1,245kg with 1% MSR, and 685kg with 10% MSR for 50㎛ particles, which demonstrates that the high capacity blowdown is an effective method of removing the bigger size particles on the tubesheet.

3.2 Discussions

SG blowdown particle size varies from plant to plant and with blowdown rates. The range of particle sizes to which more than 90% of the sludge weight was attributed, was observed at Millstone II plant to be about 0.6㎛, and Maine Yankee plant to be about 6.3㎛. Data from Fort Calhoun and Calvert Cliff plants for the specific blowdown rates indicated that 90% of the sludge weight was from particle sizes from 1.15 to 2.15㎛, and 8.4-8㎛ with the blowdown rates of 0.3-1.0% MSR and 0.08-0.75% MSR, respectively.[3] These data indicate that the particle sizes of 0.6-8㎛ range represent more than 90% of the sludge weight in the SG blowdown line during normal blowdown of less than 1% MSR. Hence, the high capacity blowdown is needed for removing the particles larger than 8 ㎛.

The drag force exerted on the particle is mainly proportional to the velocity squared times the projection area, but the particle mass increases with the cubic of the diameter. Once the particle is grown to the size which cannot be removed by the blowdown, it sticks to the tubesheet surface. The sludge which is not removed by the blowdown system, can also be removed from the tubesheet by lancing machine during the outage. The equipment is placed inside the SG and sprays high pressure (172 bar) water into the tube bundle through the lanes between tubes. A suction device removes the sludge/water slurry.

Table 1 shows the sludge lancing experiences[8]. Even with normal blowdown of 1% MSR and a high capacity blowdown of 10 % MSR for several minutes every week, the sludge of 50-100kg in about 1.5 inch thickness on the tubesheet has been regularly removed by lancing during the outage period at Palo Verde plants. But, in other plants which did not perform high capacity blowdown, much more sludge was removed by lancing. It is evident that the periodic high capacity blowdown reduces the sludge accumulation on the tubesheet.

In KSNP, the high capacity blowdown flowrate is 8.3% MSR at the hot side and 16.7% MSR at cold side. Another analysis shows that the blowdown of 8.3% MSR for 2 minutes causes the excursion of the SG water level about ±5% narrow range within the controllable range.

As the blowdown rate increases, the removable particle size also increases preventing sludge buildup in the SG. Therefore, a proper filter should be used to remove particles with normal and high capacity blowdown flow rate. When the blowdown flowrate is to be changed, it should be determined based on the operating experience data of the sludge amount and the sizes of the particles removed by the blowdown system and the sludge lancing, respectively. Also, the sludge removal capability data from this analysis can be used for the evaluation and prediction of the effectiveness of the SG blowdown in conjunction with the operating data.

4. CONCLUSION

A computational analysis has been performed to simulate the accumulation process of the iron oxide particles in the SG and to investigate the effectiveness of the blowdown on removing the particles of various sizes. From the results of this study, it is concluded:

1. The normal blowdown of 1% MSR is not sufficient for removing the particles bigger than 10 μm,
2. The high capacity blowdown is an effective means to remove the particles bigger than 10 μm,
3. The high capacity blowdown of 10% MSR reduces the sludge accumulation approximately by half,
4. The high capacity blowdown flowrate can be determined from the operational data of the sludge removed,
5. Proper filters should be used for the normal and high capacity blowdown depending the removed particle sizes.

NOMENCLATURE

C	Particle Volume Fraction
C_{2i}, C_{2j}	Inertial resistance factor in i and j direction
r_i	Radius of the inner support wall, 0.45 m
r_o	Radius of the outer wall, 1.87m
r, z	Cylindrical coordinate
μ	viscosity
ρ	density

REFERENCE

1. Ward, L.W., et. al., "INEL Technical Review of YGN 3 and 4 Thermal-Hydraulic Relative Size Effects", Idaho National Eng. Lab., 1989.
2. Beard, N.L., et.al., "Flow Induced Vibration Analysis Yonggwang Nuclear 3,4 Steam Generator Economizer and Lower Tube Bundle Region", CE Report, 1988.
3. Gwinn, R.A., "Determination of Concentrations and Particle Size Range of Iron and Copper Based Corrosion Products in S/G Secondary Water", CE Report, 1977.
4. FLUENT user's guide.
5. Syamlal, M., Rogers, W., and O'Brien, T.J., "MFIX Documentation: Volume 1, Theory Guide," DOE/METC-9411004, NTIS/DE9400087, National Technical Information Service, Springfield, VA, 1993.
6. Dalla Valle, J.M., Micrometrics, Pitman, London, 1948.
7. Park, H.S., Chung, D.M. and Baik, S.J., "Evaluation Report for the Steam Generator in the Korean Next Generation Reactor", KOPEC Report, 1999.
8. Steam Generator Secondary Side Services, ABB-CE Brochure.

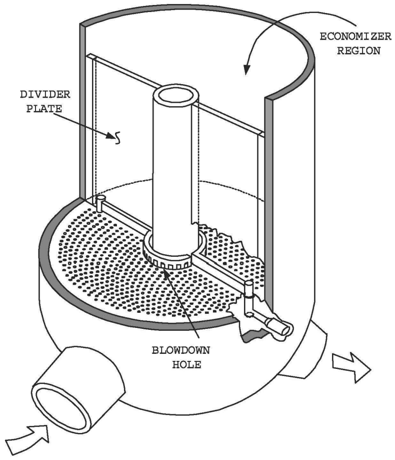
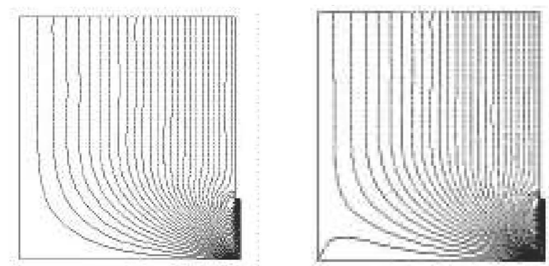


Figure 1 Steam Generator Blowdown System



(a) 0% Blowdown (b) 10% Blowdown

Figure 4 Stream Function

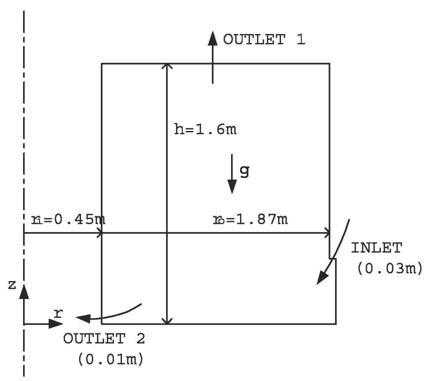
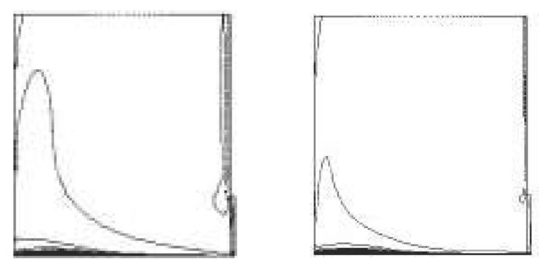
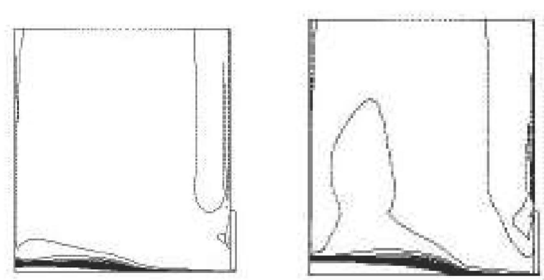


Figure 2 Analysis Model



(a) 1 ㎛ (b) 10 ㎛



(c) 30 ㎛ (d) 50 ㎛

Figure 5 Particle Volume Fraction with 1% Blowdown at t=10s (C_{min}=0.06, C_{max}=0.6, $\triangle C$=0.018)

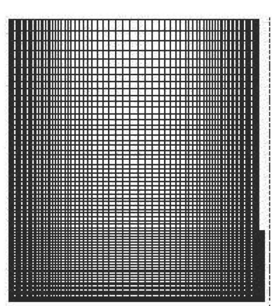
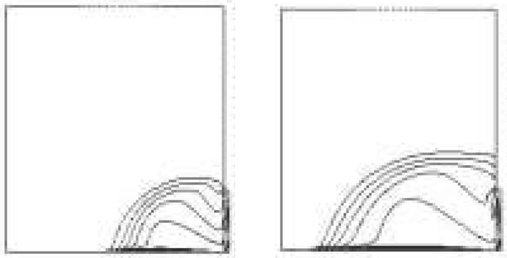
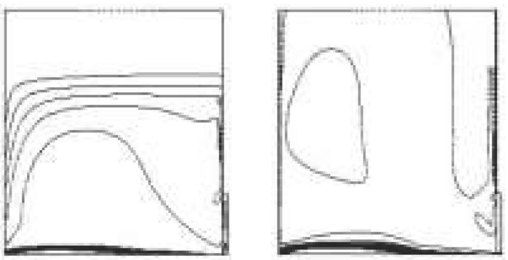


Figure 3 Analysis Grid

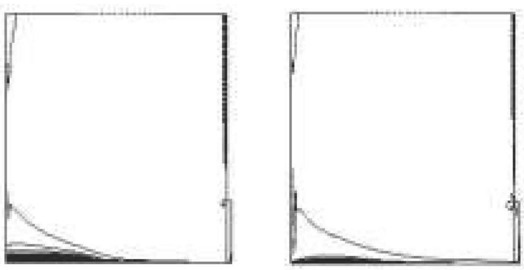


(a) 1 second (b) 2 seconds

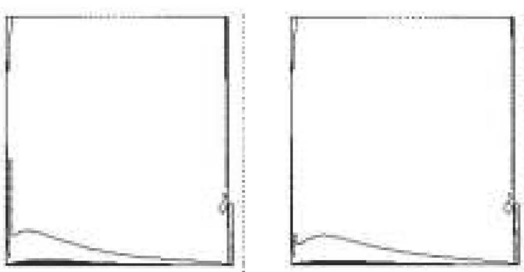


(c) 5 seconds (d) 10 seconds

Figure 6 Development of Volume Fraction of 50μm Particles with 10% blowdown (C_{min}=0.01, C_{max}=0.6, $\triangle C$=0.019)



(a) 0% blowdown (b) 5% blowdown



(c) 10% blowdown (d)15% blowdown

Figure 7 Volume Fraction of 10 μm Particles at t=10s (C_{min}=0.06, C_{max}=0.6, $\triangle C$=0.018)

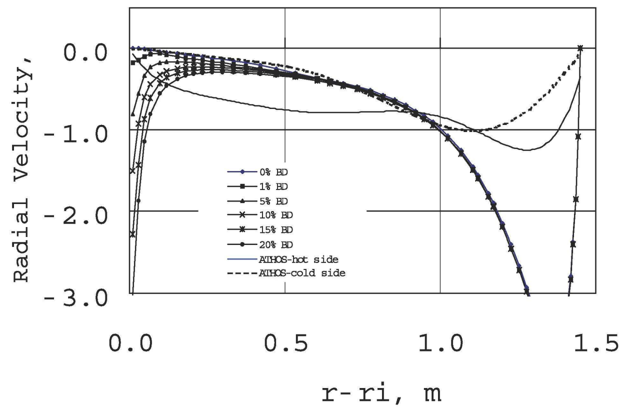


Figure 8 Radial Velocity Distribution at z=0.01m (ATHOS data[3]: 0% blowdown)

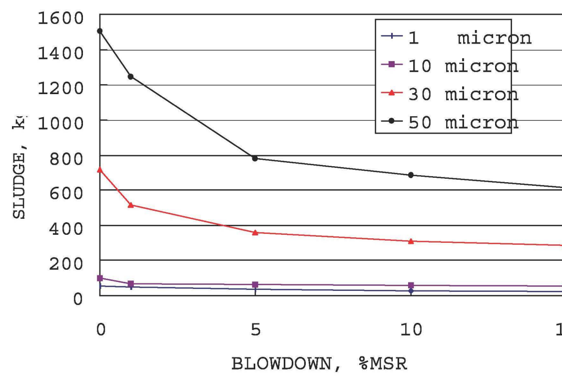


Figure 9 Sludge Accumulation on Tubesheet (t=10s)

Table 1 Sludge Lancing Experience [8]

Date	Utility/Plant	Sludge, kg
3/95	SCE/San Onofre 2	719
4/95	MY AP/Maine Yankee	2,095
8/95	SCE/San Onofre 3	469
10/95	FPL/St. Lucie 2	679
11/95	APS/Palo Verde 3	100
3/96	FPL/Turkey Point 4	369
4/96	APS/Palo Verde 2	67
10/96	CECO/Zion 2	138
10/96	APS/Palo Verde 1	98
1/97	SCE/San Onofre 2	4,728
3/97	FPL/Turkey Point 3	334
3/97	APS/Palo Verde 3	93
4/97	FPL/St. Lucie 2	383
4/97	Entergy/Waterford 3	164
5/97	Entergy/Arkansas 2	165
6/97	SCE/San Onofre 3	7,340
9/97	FPL/Turkey Point 4	327
9/97	APS/Palo Verde 2	50