< Technical Note >

DEVELOPMENT OF A STEAM GENERATOR LANCING SYSTEM

WOO-TAE JEONG*, SEOK-TAE KIM and SUNG-YULL HONG
Korea Electric Power Research Institute
Munji-dong, Yuseong-gu, Daejeon, 305-380, Korea
*Corresponding author. E-mail : wtjeong@ kepri.re.kr

Received August 17, 2005
Accepted for Publication December 21, 2005

It is recommended to clean steam generators of nuclear power plants during plant outages. Under normal operations, sludge is created and constantly accumulates in the steam generators. The constituents of this sludge are different depending on each power plant characteristics. The sludge of the Kori Unit 1 steam generator, for example, was found to be composed of 93% ferrous oxide, 3% carbon and 1% of silica oxide and nickel oxide each. The research to develop a lancing system that would remove sludge deposits from the tubesheet of a steam generator was started in 1998 by the Korea Electric Power Research Institute (KEPRI) of the Korea Electric Power Corporation (KEPCO). The first commercial domestic lancing system in Korea, the KALANS®-I Lancing System, was completed in 2000 for Kori Unit 1 for cleaning the tubesheet of its Westinghouse Delta-60 steam generator. Thereafter, the success of the development and site implementation of the KALANS®-I lancing system for YGN Units 1&2 and Ulchin Units 3&4 was also realized in 2004 for sludge removal at those sites. The upper bundle cleaning system for Westinghouse model F steam generators is now under development.

KEYWORDS : Lancing, Steam Generator, Water Jet, Pressurized Water

1. INTRODUCTION

When nuclear power plants were first introduced for generating electricity commercially in 1950s, most engineers weren't aware that sludge would accumulate in the steam generators. Therefore, some early steam generator models during the 1950s and 1960s were even built without hand-holes for inspection and sludge removal. However, with the experience of operating commercial nuclear power plants, the engineers acknowledged that periodic removal of sludge from nuclear steam generators was necessary.

Sludge accumulation in the secondary side of nuclear steam generators may cause tube degradation. Soft sludge can harden when it is baked by the hot temperature of the primary coolant. Soft and hard sludge prevent heat transfer from steam generator tubes to the secondary side coolant, and hence may influence the electricity production in power plants[1]. Therefore, steam generator makers recommend that the secondary side of the tubesheet and the tube support plates should be cleaned during each outage[2].

There are several ways to clean nuclear steam generators. Pressurized water jets are most often utilized to remove sludge. Cavitations caused by water-immersed ultrasonic transducers are often used to soften hard sludge. Chemicals to selectively dissolve sludge without damaging the internal components of a steam generator have also been used in nuclear utilities. Upper bundle flushing is also an efficient way to remove soft sludge that has accumulated in the upper regions of steam generators.

2. SLUDGE ACCUMULATION

The dominant sludge constituent, ferrous oxide, is created by wear and corrosion of the pipes and the components comprising the secondary side of the nuclear power plant. Sludge contained in the secondary side coolant comes into the steam generator through the feed water line. The flow velocity in the central region of the tubesheet is nearly zero; thus, comparatively heavy solid components, such as ferrous oxide, are separated from the coolant and accumulate. Soft sludge separated from the feed water and deposited on the tubesheet is heated to more than 200 degrees Celsius during the operation of the plant. Furthermore, the two-phase flow phenomena on the tubesheet further promote solidification of the soft sludge. Consequently, hard sludge is created in the kidney bin zone of nuclear steam generators if soft sludge is not removed effectively during a plant outage. Once a hard sludge has formed, it is difficult to remove.

3. TUBESHEET LANCING

3.1 The KALANS®-I Lancing System

KEPRI started the design of the lancing system in 1999 to clean the Westinghouse Delta 60 steam generator, and completed the manufacturing and site implementation on October 2000[1]. The developed lancing system was given the acronym KALANS®-I (Kepco Advanced Lancing System). KALANS® is a registered trademark of the KEPRI steam generator cleaning system. The project for developing KALANS®-I lancing system was supported by KHNP (Korea Hydro & Nuclear Company).

250 bar of pressurized water is supplied to the nozzle head of the lancing robot, as shown in Figure 1, and is ejected through eight nozzles into the gap between steam generator tubes. The lancing robot is guided by a rail installed in the no-tube lane of the steam generator. By the rotation of a pinion gear connected to a servo motor with an encoder, the entire lancing robot moves along the rail in the steam generator. Another servo motor axis is directly coupled to the nozzle head in order to enable the rotation of the nozzle head. A video-scope is attached to a camera mount to provide a video image to the operator [1].

The control system of KALANS®-I consists of the KALANS® Master, the KALANS® Servo and the robot, as shown in Figure 2. The KALANS® Master is an industrial computer with a sound card and a frame grabber having a 3-d accelerator. The KALANS® Master sends robot command data to the KALANS® Servo and receives robot status data via an Ethernet link. The KALANS® Servo is the other industrial computer with a DAS (data acquisition system) and a motor signal amplifier. It is directly connected to the lancing robot.

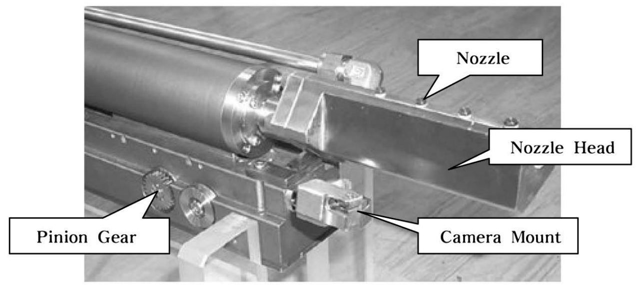

Fig. 1. KALANS®-I Lancing Robot

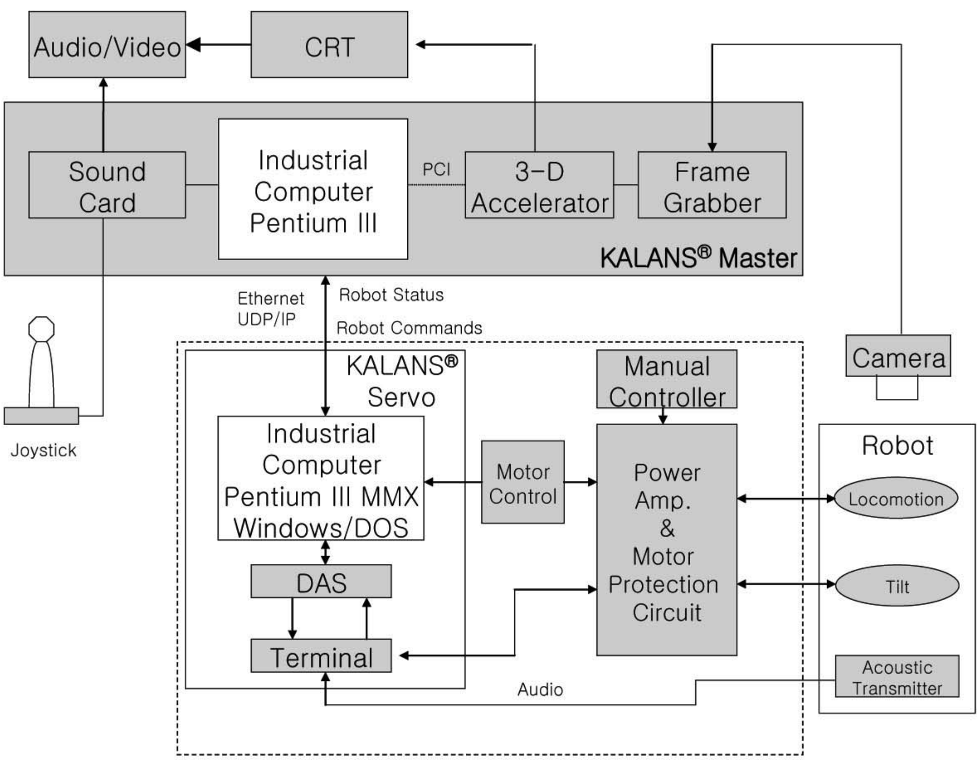

Fig. 2. KALANS®-I Control System Architecture

3.2 KALANS®-II Lancing System

The previous lancing system for the Optimized Power Reactor (OPR-1000), an evolutionary type of System-80 steam generator, was inefficient for the removal of accumulated sludge from the steam generator tubesheet. Pressurized water was directed from the annulus toward the center; therefore sludge accumulation in the central area of the steam generator tubesheet, sometimes called the kidney bin zone, was often observed to be increased after lancing. To remove the sludge accumulating in the kidney bin zone, a very novel rail and a lancing nozzle head were designed, and are shown in Figure 3.

The System-80 steam generators have an economizer divider plate along the no-tube lane. Furthermore, there is a stay cylinder in the center of the steam generator. The divider plate separates the cold and hot sides, and is connected to the stay cylinder. To automate the operation of the lancing system, a rail was designed that can be installed along the no-tube lane through the handhole with the help of the lance guide. The rail is designed to be installed on the left and right sides of the stay cylinder. The end portion of the rail is segmented into several parts so that it can be bent. The rail guide causes the rail to bend at 45 degrees. Before installing the rail into the handhole of the System-80 steam generator, a handhole fixture should be attached to the handhole using several hex bolts. The gap between the divide plate and the tube bundle of the System-80 steam generators averages approximately 33.2mm. The rail and the rail guide are designed to be installed along this gap; thus, the maximum width of the rail and the rail guide are limited to 33.2mm, theoretically. The lances, which eject pressurized water, are designed to move along the groove in the rail. The movement of the lance is controlled by a servo motor. A timing belt is attached to the lance, and this belt is controlled by a pinion gear driven by a servo motor. The timing belt is selected to drive the lance as it can bend easily.

The lances have various nozzles which can eject pressurized water into the sludge that accumulates on the tubesheet of a steam generator. Several different lances were designed, depending on the requirements of each lance. Two lances move along the rail simultaneously, and go into the left and right side of the stay cylinder. A pressurized hose is connected to the lance to supply water that discharges through the nozzles attached at the lance. The hose connection to the lance is designed to enable it to swivel. To minimize the pressure drop along the swivel joint while maintaining the pressure boundary, a new pressurized water connector was designed and created[3].

The other four lances only move along the linear portion of the rail. The eject angles with respect to the rail are set as 30 degrees and 90 degrees. To effectively remove the shadow zone effect, two lances out of the four have nozzles with 30 degree ejection angles; whereas the remaining two have nozzles with 90 degree ejection angles with respect to the rail.

The handhole mount is designed to facilitate an easier and quicker installation and removal. The handhole mount can be attached to the handhole by only four hex bolts. The rail guides are attached to the handhole mount through grooves in the triangular shape built onto the guides. A total of three guides are attached along the stem of the handhole mount. The rails are attached to the rail guides by grooves built into the rail guides. The rails have rectangular shaped-grooves that guide the movement of the lances.

The difficulty in designing a lancing system arises from the uncertainty of the dimensions of the components of steam generators. A steam generator is such an enormous

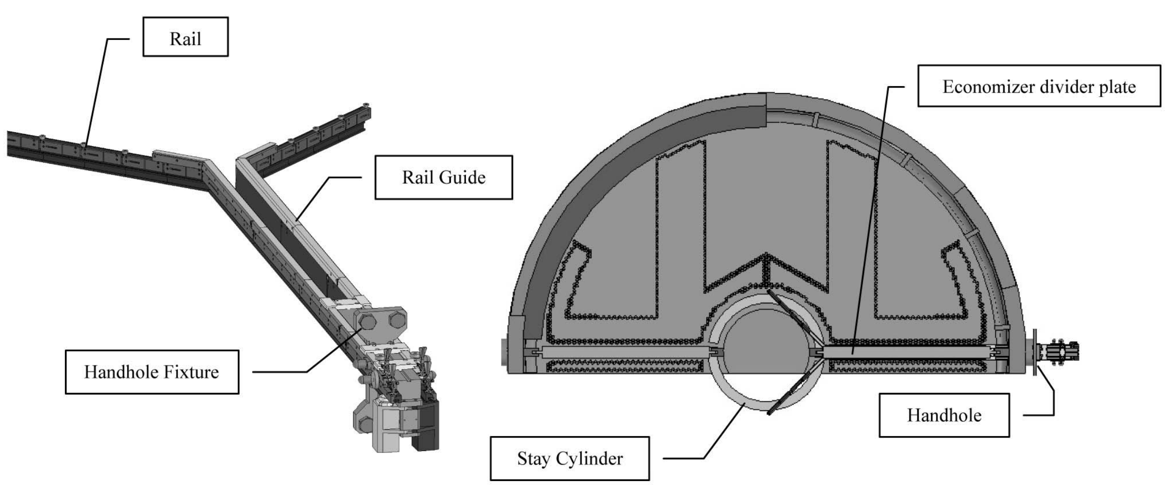

Fig. 3. Lancing System (left) Installed in the System-80 Steam Generator (right)

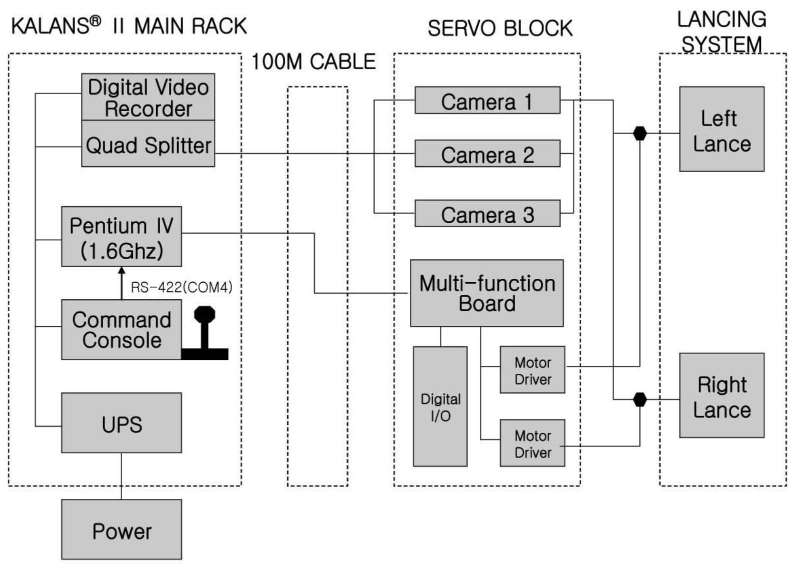

Fig. 4. Block Diagram of Control System

component that the exact dimensions are often ignored. Unexpected dimensional discrepancies in steam generator components often create confusion for the design engineers of the lancing system.

The control system consists of a control computer, a video monitor, a computer monitor, a command console, communication cables and a servo block, as shown in Figure 4. Communication cables connect a servo block, located in a CV (Containment Vessel), to a control computer outside of the CV. The servo block supplies power to the servo motors to drive the lance, and transfers camera images from inside the CV to the main computer. The control computer controls the lance and communicates with the servo block. The computer also monitors the position and the status of the lance. The computer is composed of a Pentium IV 1.6GHz processor and 256MB RAM. A DVR (Digital Video Recorder) and a quad splitter are used to recode the images from the cameras. A quad splitter enables images from several cameras to be displayed on a single monitor. The command console in the main rack has a joystick and several switches that enable remote control of the lance. A UPS (uninterrupted power supply) in the main rack provides power to the system without interruption in the event of an unexpected shut down.

Figure 5 shows the control system hardware. Monitor 1 at the top of the main rack is 19 inches in size and displays an image of the DVR. The display is divided into four regions by the quad splitter (not shown here). A video image is digitally recorded by the DVR. The recordings can be monitored through the computer. Monitor 2 is a 17-inch computer display. A joystick and several switches on the command console enable an operator to control the lance.

A steam generator mock-up was developed in order to test the developed water jet lancing system. Several cold tests were made at KEPRI during the first few months of 2004 using this mock-up. The lancing system and the mock-up were then transported to Ulchin Unit 3. The first site implementation was completed in April of 2005. The installation and operation of the developed lancing system was completed by KPS (Korea Plant Service & Engineering Co). personnel who are responsible for lancing. Approximately twelve people were involved in the cleaning service, and

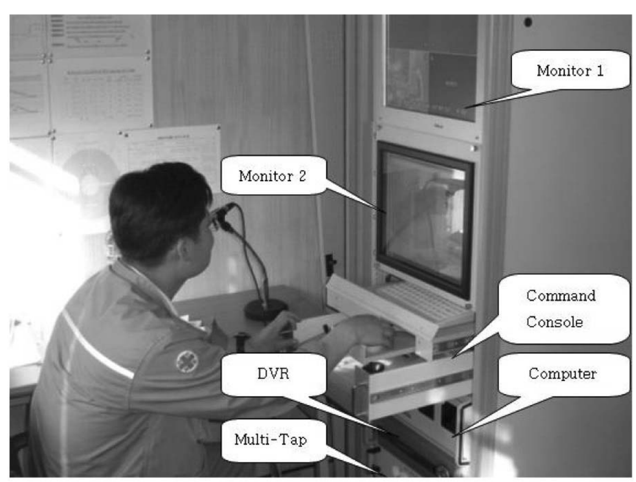

Fig. 5. Control System

nearly ten days were required to clean two steam generators at Ulchin Unit 3. The weight of removed sludge approached 12 Kg. The second application of the lancing system for Ulchin Unit 4 was successfully completed in January of 2005. Figure 6 shows the lancing system installed on the handhole of the System-80 steam generator of Ulchin Unit 3.

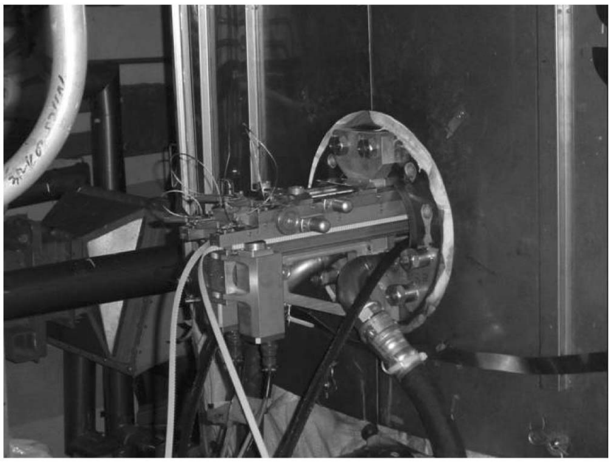

Fig. 6. KALANS®-II Lancing System Installed on the System-80 Steam Generator of the Ulchin Units 3 & 4

3.3 KALANS®-III Lancing System

As the outage durations were becoming shorter each year, a new lancing system for the simultaneous removal of soft sludge and hard scale was developed in 2004 specifically to clean the tubesheet of Westinghouse model F steam generators. The nozzle head assembly has 12 barrel spray nozzles and a rigid lance to facilitate the removal of soft sludge and hard scale, respectively. This is shown in Figure 7. 650 bar of pressurized water from the rigid lance breaks the hard scale on the tubesheet or on the tube surfaces. The rigid lance was designed to be inserted into the gap between the tubes in order to transfer as large a momentum as possible to the hard scales.

When the nozzle head assembly is inserted into the secondary side of the steam generator, the rigid lance is folded to enable it to move through the handhole with its inside diameter of six inches. Once inside the steam generator, the rigid lance unfolds. The nozzle head assembly is attached to the locomotion robot which moves along the rail. The pinion gear on the locomotion robot is directly coupled to a rack gear of the rail. A servo motor with an optical encoder rotates the pinion gear, thus an exact positioning of the nozzle head assembly is possible.

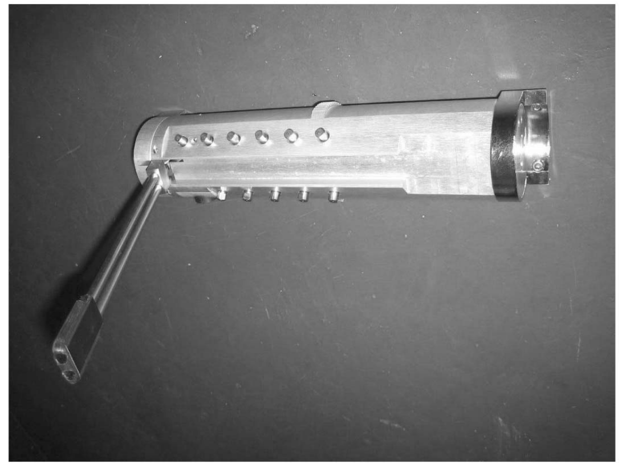

Fig. 7. KALANS®-III Nozzle Head Assembly

Safety of operation of the lancing system is the most important factor to be considered during the design stage. The KALANS®-III Lancing System has several unique safety features. First, the two bevel gears transmitting the rotational motion of the servo motor of the lancing robot are designed to be mechanically disengaged. This feature enables the operator to remove the nozzle head assembly from inside the steam generator if the lancing robot jams during the steam generator lancing. Secondly, the operator is able to rotate the nozzle head assembly mechanically using a special tool if the assembly becomes wedged between the tubes while lancing the hard scale. The architecture of the control system is similar to that of the KALANS®-II Lancing System.

3.4. Upper Bundle Cleaning

Accumulation of soft sludge on the tube support plates often blocks the broach holes. Blocked broach holes may prevent steam flow from the bottom to the top of the steam generator. Therefore, an upper bundle cleaning system was developed to remove the accumulated sludge from the tube support plates and from the broach holes.

The upper bundle cleaning system is composed of a nozzle head, a hydraulic cylinder, a support rail, a sludge processing system, and a control system, and is shown in Figures 8 and 9. A support rail is installed through a handhole of the steam generator. A hydraulic cylinder moves upward through the flow slot on each tube support plate. On the top of the hydraulic cylinder, the nozzle head assembly is attached. When the nozzle head assembly reaches the cleaning position, it is disengaged from the hydraulic cylinder. The hydraulic cylinder and the nozzle head assembly are temporarily joined by an electromagnet.

When the nozzle head assembly is placed on a desired tube support plate, it is separated from the hydraulic

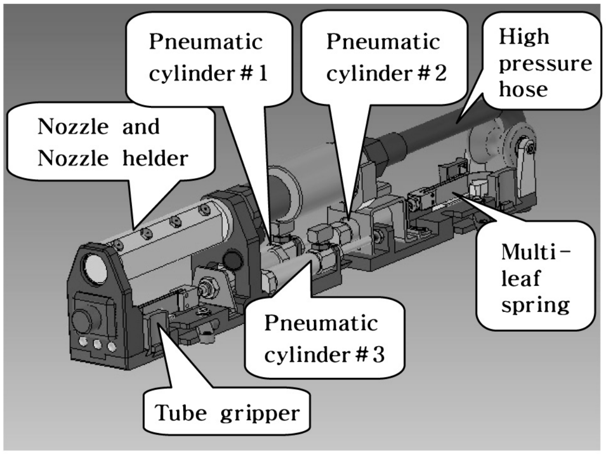

Fig. 8. The Nozzle Head Assembly

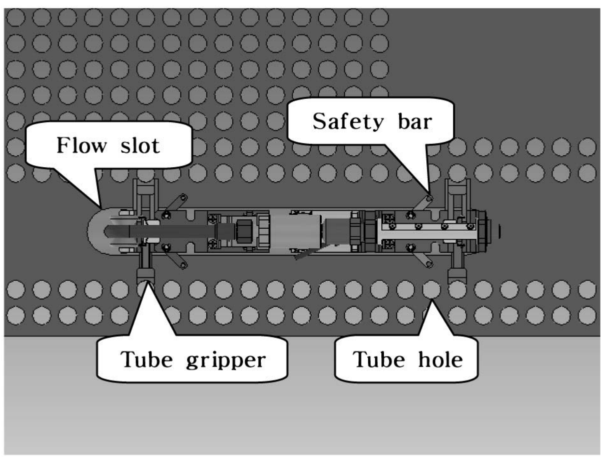

Fig. 9. Nozzle Head Assembly on the Tube Support Plate

cylinder when the power to the electromagnet is switched off. Two pairs of tube grippers are sequentially activated by pneumatic cylinders #1 and #2. When one tube gripper is retracted, the nozzle head assembly moves along the no-tube lane as a result of the activation of pneumatic cylinder #3. Pressurized water is supplied through the water hose. Water is ejected through multiple nozzles on the nozzle holder while the two tube grippers firmly hold the tubes of the steam generator.

3.5 Sludge Processing System

A sludge processing system for the upper bundle hydraulic cleaning was designed and manufactured. This system is composed of a suction pump, a surge tank, a storage tank, a transfer pump, a filtering system and a high pressure water pump, and is shown in Figure 10. The suction pump absorbs sludge from inside the steam generator. The sludge is stored temporarily in the surge tank. The transfer pump sends sludge to the filtering system. The filtering system is composed of two stages of filters with a mesh size of 1 and 10 microns. A high-pressure water pump pressurizes water to 260 bar and sends it to the nozzle head assembly.

3.6 Water Jet Nozzle

To devise a nozzle for a lancing system, several nozzles were designed and manufactured, as shown in Figure 11. The nozzles used for the experiment were 1.2mm in diameter and had an aspect ratio of 3, this being the ratio between the length of nozzle tip and the exit diameter of the nozzle. d_0 is the nozzle outlet diameter, as shown in Figure 11.

Figure 12 shows the experimental setup used for testing the high-pressure water jet nozzles. The setup is composed of a fluid supply system, a data acquisition system and a suction system. The test zone (0 to 1200mm) is covered with a flow channel that has a transparent window. Two pressure

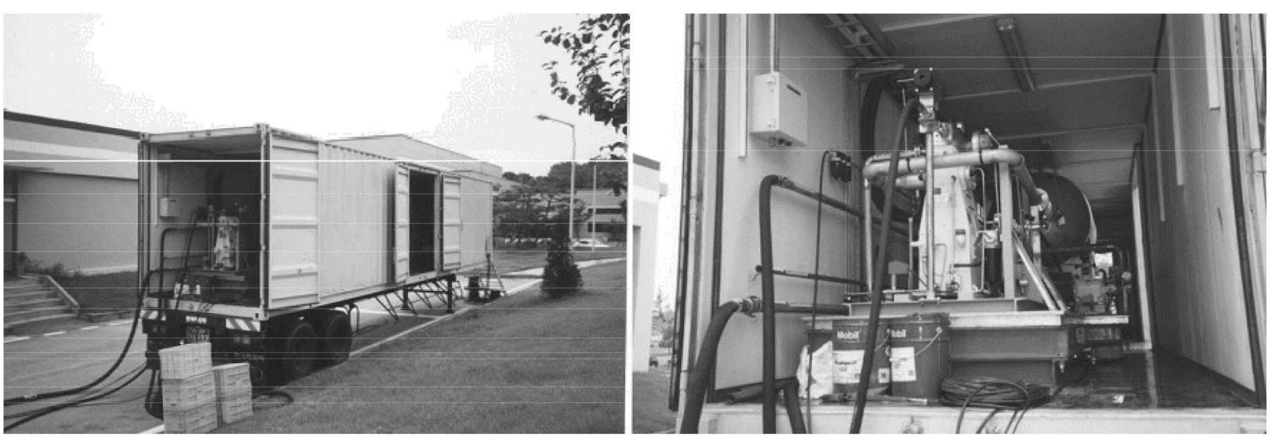

Fig. 10. Sludge Processing System

sensors [Hydro-Technik; 250 bar (HT-250), pressure-Systems; 17 bar (PS-17)] were used for the data acquisition. The HT-250 was used to measure the nozzle chamber pressure, and the PS-17 was connected to a Pitot-tube (diameter = 8*mm*) to measure the jet static pressure. Figure 13 shows the experimental setup that tested the flow characteristics of the high-pressure water jet nozzles

Figure 13 shows the pressure distribution with respect to the aspect ratios and the inlet flow rates. The X in the figure designates the horizontal distance in millimeters from the nozzle outlet to the measurement position. Higher inlet flow rates at the same aspect ratio produce high pressure at the nozzle outlet, as shown in Figure 13(a). However, a higher aspect ratio causes a drop in pressure at the nozzle outlet, but the magnitude is small, as shown in Figure 13(b).

4. CONCLUSIONS

Since March of 1999, KEPRI has been developing various water-jet lancing systems for cleaning nuclear steam generators. The first lancing system in Korea, the KALANS

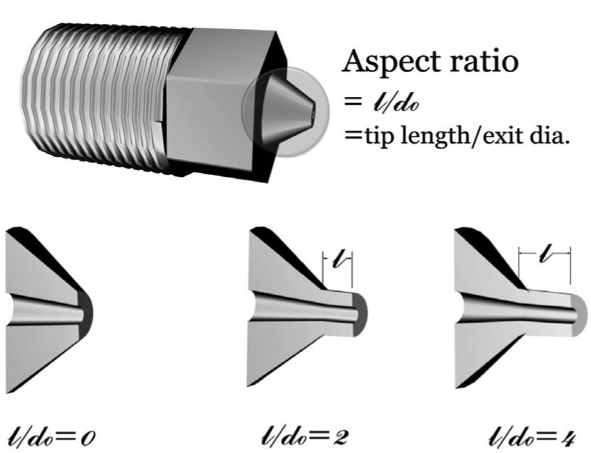

Fig. 11. Schematic Diagram of the Experimental Nozzles

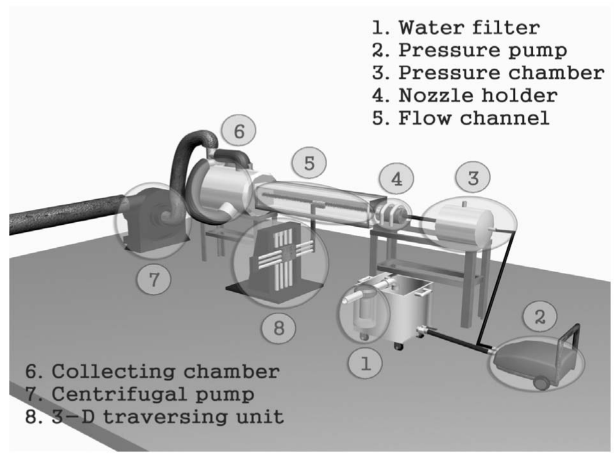

Fig. 12. Experimental Setup of High-Pressure Water Jet System

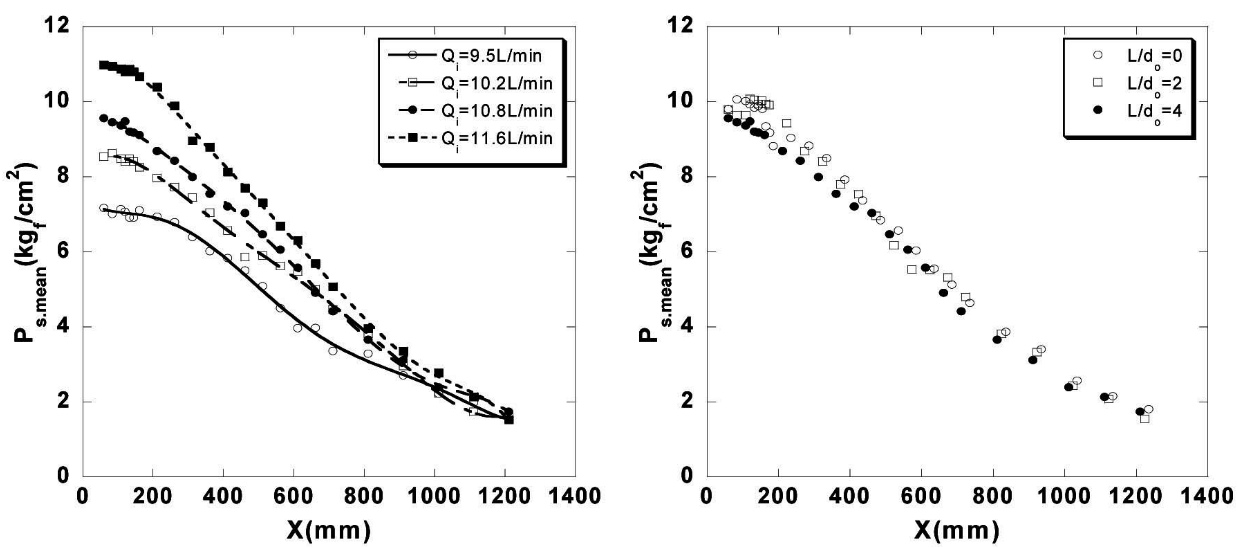

Fig. 13. Pressure Distributions; (a) $L/d_o = 4$, (b) $Q_i = 10.8$ *liters/minute*

®-I Lancing System, was developed and successfully used in 2000 to clean the tubesheet of the Kori Delta-60 steam generator. A sludge processing system was also developed to supply pressurized water and to remove solid ingredients from the sludge. The KALANS®-I Lancing System has been used for the lancing of the Delta-60 and Model-F steam generator of Kori Units 1 & 2 since 2000.

The project to develop steam generator lancing systems for Ulchin Units 3 & 4 and YGN Units 1 & 2 was started in 2001 and completed in 2004. The KALANS®-II Lancing System of Ulchin Units 3 & 4 was designed to effectively remove sludge accumulated in the kidney bin zone of the tubesheet. The lance was designed to move along the rail installed between the divide plate and the tube bundle. The KALANS®-III Lancing System of YGN Units 1 & 2 was designed to be able to remove soft sludge and hard scale simultaneously. This unique feature enables lancing in the relatively short time of one day per steam generator. Therefore, the lancing of a steam generator may be completed in three days using the KALANS®-III Lancing System.

During the upper bundle inspection of the Model-F steam generators of Kori Units 3 & 4, sludge was observed to have nearly blocked the broach holes of the tube support plates. To remove the sludge and scale blocking the broach holes, the development of upper bundle lancing technology started in 2003. The nozzle head assembly is designed to be lifted by a hydraulic cylinder through a flow slot. The assembly is fixed on the tube support plate, and ejects pressurized water that removes sludge in the broach holes and on the tube support plates.

Several nozzles were designed and tested during the selection of the appropriate nozzles for each lancing system. However, it was found that the aspect ratio was not the dominant factor affecting pressurized water ejection, and it was observed that a smooth surface finish is necessary in order to provide a stable, straight and converging water jet.

REFERENCES

[1] W.T. Jeong et al., “Development of Sludge Lancing System for Delta-60 SG,” Internal Technical Report, KHNP, (2002).

[2] Vertical Steam Generator Instructions for Korea Electric Power Corporation Kori Nuclear Power Plant-Unit 1, Westinghouse Electric Company Technical Manual, (1997).

[3] W.T. Jeong, S.T. Kim and S.Y Hong, “Development of Sludge Lancing System for Younggwang Unit 1 & 2 and Ulchin Unit 3&4 Steam Generators,” Internal Technical Report, KHNP, (2004).