KEPAR FGD MODEL TEST AND VERIFICATION

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1. KEPAR Basic Concept

The Korea Electric Power Corporation Absorption Reactor (hereinafter KEPAR) is a new type of SO_2 absorber conceived and developed by Korea Electric Power Corporation Research & Development Institute (hereinafter KEPRI). The absorber combines the features of a bubbler and a sieve tray in a unique way to achieve gas/liquid contact and SO_2 removal. Using inexpensive limestone as the reagent and utilizing forced oxidation to produce salable-grade gypsum, the KEPAR is the key component of FGD systems retrofitted to fossil fuel-fired boilers up to 200 MW size at several of KEPCO power plants in Korea.

The basic components of the KEPAR are shown in Figure 1. The working principle of each component is described below.

Flue gas enters the KEPAR after being quenched in a presaturator upstream. The saturated flue gas enters the dirty gas plenum and passes through a tube sheet in the floor of this plenum into numerous duct pipes. The duct pipes carry the flue gas down to the lower deck, which consists of a compartmentalized perforated plate sieve tray, which is submerged in the slurry reaction tank. The duct pipes are seal welded to the sieve tray plate such that flue gas initially discharging from the pipes as large-scale bubbles must displace slurry from below the sieve tray. The displaced slurry is transferred to the liquid layer above the sieve tray through riser pipes, which extend from the tank beneath the gas layer to and through the sieve tray.

The expanding gas layer, which forms beneath the sieve tray as bubbles from adjacent duct pipes combine is confined by a weir plate which, surrounds each compartment. In order to escape this confinement the gas must pass upward through the sieve tray gas holes. High velocity jets of gas passing from the confined gas layer through the gas holes in the submerged sieve tray fluidize the slurry above the tray, providing contact between the gas and the liquid which leads to SO_2 absorption.

The liquid at the tray surface is sheared into large drops which are thrown upward from the sieve tray gas holes. As the gas rises and expands into the region above the sieve tray the resulting velocity reduction allows the droplets to fall. This action forms a very active region in which droplets are constantly rising above and falling back to the tray surface. As the gas rises further above the sieve tray all but the smallest droplets are able to fall back to the sieve tray. The clean gas then leaves the KEPAR by exiting out the side of the clean gas plenum. Residual entrained droplets are removed by an external horizontal-flow mist eliminator.

The same weir plate which confines the gas layer below the sieve tray for each compartment also extends above the tray surface. In this region it serves to contain the active two-phase flow, allowing extended contact time between the gas and liquid. As liquid splashes over the weir it is returned to the tank by gravity flow in the downcomers which are formed by the space between the weir plates of adjacent compartments.

Due to the gas-side pressure drop across the sieve tray and the suspended liquid, a significant pressure differential is established. The high pressure in the gas layer and the low pressure in the clean gas plenum above the sieve tray result in development of a hydrostatic head between the liquid level in the downcomers and the liquid level beneath the gas layer inside the compartments. This hydrostatic head provides a driving force for slurry to flow up the riser pipes. The spent slurry which splashes over the weir into the downcomers is replaced by fresh slurry from the reaction tank supplied to the gas/liquid contact zone through the riser pipes.

The limestone slurry and the oxidation air are supplied to the reaction tank, where the functions of neutralization, oxidation, and gypsum crystal precipitation and growth occur. These functions of the reaction tank are similar to those found in other SO_2 absorber types utilizing the limestone forced oxidation process, and are not the subject of this paper.

The unique aspects of the KEPAR include the liquid recirculation mechanism as described above and the fact that this recirculation is achieved without the use of pumps, piping systems, or nozzles. Recirculation rate in the KEPAR is a function of pressure differential and liquid inventory, which can be adjusted easily to obtain a wide variation in hydraulic performance. Absorber types, which rely on pumps to achieve liquid recirculation, can typically only effect step changes in recirculation flow by turning on additional pumps.

2. Stages of Development

The development of the KEPAR has moved from initial concept development through bench scale and pilot scale testing to the construction of a full-scale demonstration plant of Youngdong Unit 2. More information about the steps in the development of the KEPAR is provided below.

2.1 Bench Scale Tests

Two types of bench scale tests were performed by KEPRI researchers in the initial development of the KEPAR concept. The first type of test involved the study of the dynamics of bubble formation and spreading due to gas flow from a single duct pipe in the center of a sieve tray submerged in a 1.5-meter diameter water tank. This simple model was designed to determine the extent to which a gas layer can be expected to form under the sieve tray using various duct pipe diameters and gas flows. The tray used in this device had the same gas hole diameter and open area as the bench scale model and subsequent full-scale designs, but did not have downcomers or riser pipes. The results of these tests were subsequently used by KEPRI to develop the spacing criteria for the duct pipes in the pilot scale and full-scale design.

The second kind of bench scale tests was conducted to study the SO_2 removal performance of the KEPAR. The bench scale reactor used for these tests was 600 mm in diameter and included three small duct pipes. The weir was located at the perimeter of the lower deck sieve tray, with the downcomer then formed by the space between the weir and the outer wall of the absorber. The gas flow range of this model was 750 to 1500 Nm^3 per hour (0.4 MW equivalent). A slipstream of flue gas from the Youngdong power plant was used as the source of flue gas.

Design features evaluated for their effect on performance included riser pipe diameter, sieve tray gas hole size, weir heights above the tray and weir plate depth below the tray. Operating parameters studied included tank pH, initial liquid level above the tray, gas flow and absorber differential pressure.

The test results indicated that the KEPAR concept provided good gas/liquid contact and achieved SO_2 removals well above 90 percent up to almost 99 percent. The bench scale tests were also used to provide data on KEPAR hydraulic performance factors such as the froth height above the tray. Based on the positive results of the bench scale testing the next stage of development was begun.

2.2 Pilot Plant Tests

A 10 MW KEPAR pilot plant was constructed at the Youngdong Power Plant to prove the concept of the KEPAR absorber as a component of a FGD system. The gas flow for the pilot plant was 35,000 Nm^3/hr. The ductwork was configured to allow the use of actual flue gas from either Youngdong Unit 1 or Youngdong Unit 2.

The pilot plant KEPAR was 3.0 meters in diameter and included the use of components, which were the same size and design as those being planned at that time for full-scale KEPAR units. These components included the duct pipes, riser pipes, weir plate dimensions (above and below the tray), sieve tray gas hole size and percent open area. The layout of the lower deck of the pilot plant KEPAR was similar to that used for the bench scale testing, with the downcomer formed by the annular space between the weir around the lower deck and the outer wall of the absorber.

The pilot plant was configured to include most of the required components of a full-scale FGD system, including booster fan, inlet flue gas presaturator and outlet flue gas mist eliminator, limestone powder storage silo, mixing tank for reagent slurry preparation, reagent slurry feed pumps and piping systems, oxidation air blowers, and sparger system. A rudimentary gypsum dewatering system was included.

The test program for the pilot plant included investigation of the effect of the following operating parameters on performance:

- Oxidation air molar ratio
- Limestone grind
- Operating pH
- Absorber ΔP

The results from the pilot plant testing generally validated the basic process design. The KEPAR was shown to be capable of achieving SO_2 removal efficiencies above 95 percent. Removal efficiency was shown to be a primarily a function of absorber ΔP and pH. The purity of the gypsum produced was consistently above 95 percent $CaSO4 \bullet 2H_2O$. Finer limestone grind (90 percent passing 325 mesh) was found to enhance both removal efficiency and gypsum purity when compared to coarser grind (90 percent passing 200 mesh). Oxidation air molar ratios above 2.5 moles O_2 per mole SO_2 were shown to produce negligible improvements in performance.

2.3 Demonstration Unit

Coincident with the testing of the 10 MW pilot plant by KEPRI, Korea Power Engineering Company Inc. (hereinafter KOPEC) began the design of a full-scale retrofit FGD system for the 200 MW Unit 2 Youngdong Power Plant which is intended as a demonstration plant for the use of the KEPAR. The KEPAR for Unit 2 is 14.3 meters in diameter. The design flue gas flow rate is 800,000 Nm^3/hr. As the design of the demonstration unit and the testing of the pilot plant proceeded, certain scale-up issues arose which resulted in the reconsidering of some of the design aspects of the KEPAR. The next section describes these issues, and the basic design revisions they precipitated.

3. Scale-up Issues

During the course of the development of the design for the Youngdong Unit 2 demonstration unit, the importance of differing characteristics between the full-scale design requirements and those previously used for the pilot plant came into focus for the developers of the KEPAR.

3.1 Areas of Concern

Due to the large jump in size from the 10 MW pilot plant to the 200 MW demonstration unit some aspects of the design and operation of the KEPAR which were not considered in the pilot plant became critical issues. Some of these are:

- Maintenance of adequate recirculation rates

In the KEPAR, as in any wet limestone process SO_2 absorber, the recirculation of "spent" slurry to the reaction tank, and its replacement in the gas/liquid contact zone with "fresh" slurry, is important to the success of the process. Inadequate recirculation can lead to reduced removal efficiency and other problems, including chemical scaling. The direction of the design of the 200 MW KEPAR was reevaluated to address the following aspects of recirculation rates:

- In the KEPAR, recirculation rates will be determined in large part by the flow or splashing of slurry over the weir. As the pilot plant design (which had a weir only at the perimeter of the lower deck) is scaled up to larger sizes, the ratio of weir length to active gas/liquid contact area above the tray will go down. This will presumably result in reduced flow over the weir, and lower recirculation rates.

- Data from the pilot plant indicated that the pH drop from the bulk slurry in the reaction tank to the slurry overflowing the weir was greater than in the bench scale testing. This may be indicative of reduced recirculation rates. Continuation of this trend could result in performance problems in the full-scale system.

- Initial designs for the 200 MW KEPAR included the provision for additional rings of downcomers concentric to the perimeter weir, to provide increases in the weir length to active area ratio. However, because these downcomers had not been modeled at the pilot plant the effect on recirculation rates was uncertain.

- Unknown operating characteristics at reduced load

The pilot plant was primarily operated only at full load, so the behavior and performance of the KEPAR at reduced loads was not known.

- Need for increased margin of safety for SO_2 removal efficiency

The pilot plant had operated in the "wet stack" mode, with a separate stack provided to handle the flue gas discharge. However, in the full-scale KEPAR there was a requirement to provide stack gas reheat for the reduction of the frequency of occurrence of a visible plume. The reheat method selected was a Ljungstrom-type rotary GGH located between the booster fan and the KEPAR. The expected leakage of untreated flue gas to the clean gas side of the GGH meant that the absorber SO_2 removal would need to be increased somewhat to compensate. This factor heightened concerns about the uncertainty in performance of the scale-up of the KEPAR from 10 MW to 200 MW.

3.2 Resultant Design Revisions

In order to address the scale-up concerns identified above, KEPRI initiated the following design revisions to the basic design of the KEPAR:

- Change to modular compartmentalized arrangement of lower deck sieve tray

The design concept for layout of the lower deck of the KEPAR was changed to provide for compartmentalization of the lower deck. This concept, as shown in Figure 2, would allow for significant increases in the weir length to active area ratio compared to the design of the pilot plant or the initial concepts for layout of Youngdong Unit 2.

- Change in duct pipe configuration from "honeycomb" to "rectangular".

Associated with the change to the rectangular module concept the relative arrangement and size of duct pipes and riser pipes was changed. The previous "honeycomb" (hexagonal) arrangement as shown in Figure 3 is contrasted to the new rectangular arrangement shown in Figure 4 .

3.3 Commercial Development

Another notable scale-up issue was that the commercial development of the KEPAR was proceeding ahead of the completion of the demonstration of Young Dong Unit 2. KOPEC had been authorized by KEPCO to proceed with design projects for KEPAR-based FGD systems for three additional units. But the ultimate effect of the design changes in the Unit 2 demonstration project on performance were not determined because the start-up of the demonstration unit was not performed until the commercial units installed.

4. Need for Verification Study

By the time the design modifications to the KEPAR had been developed by KEPRI and communicated to KOPEC, the 10 MW pilot plant was no longer operational. Due to construction activities at the Youngdong plant it was not possible to continue operation of the pilot plant. In any event, since the pilot plant design did not represent the revised design arrangement, extensive revisions to the pilot plant KEPAR would have been needed to allow its use in evaluation of the changes. Consequently, KOPEC identified the need for a verification study, including scale model testing, to accomplish the following goals:

- Verify performance of KEPAR design concept changes made after the 10 MW pilot plant program.
- Evaluate performance over ranges not covered in 10 MW pilot plant
- Investigate effects of design and operating parameter changes on KEPAR performance
- Understand mechanisms for KEPAR operation and process control
- Provide data for development of a computer model which could be used for scale-up of KEPARs in the future.

5. Scope of Model Testing

In December 1996, KOPEC contracted with Burns & McDonnell (B & M) to perform the KEPAR model test and verification. The model testing was performed by United Pacific Technology of Seoul, Korea as a subcontractor to B & M. B & M also retained DynaFlow Systems to provide consultation on the conduct and interpretation of the model tests. Two kinds of model tests were conducted. The scope of each is described below:

5.1 Gas/Liquid Model Tests

The first kind of model test conducted was the gas/liquid model tests. Two different gas/liquid models were constructed and tested. Each model was nominally a 1/8-scale model of the full-size KEPAR component it represented. These models were operated on air and water only in order to evaluate the ability of the newly revised absorber design to perform the required functions of liquid-to-gas contact, gas distribution and liquid flow distribution over the required range of operating conditions. The models were also used to investigate the aerodynamic and hydraulic performance of the critical absorber components, which are essential to scale-up or scale-down of the KEPAR.

Model of a single square module: The first gas/liquid model tested was a half-size version of a single square KEPAR module based on the revised design layout developed by KEPRI. This model was used to evaluate the hydraulic performance of key components of the KEPAR. The primary purpose of this model was to evaluate two-phase flow on and above the lower deck sieve tray. Thus the components of this model in the immediate vicinity of the lower deck (riser pipe, downcomer, weir, and divider plate) were constructed at the full-scale dimensions to provide proper hydraulic simulation of the two-phase flow. The configuration of the single square model is shown in Figures 5 and 6.

The flow characteristics which were studied using the single square scale model included:

- Gas distribution to and through the duct pipes
- Gas distribution below and through the lower deck sieve tray (gas layer)
- Liquid flow from the tank, through the riser pipes and onto the tray
- Froth or spray characteristics above the tray
- Froth or spray flow to and over the downcomer weirs
- Gas flow distribution from the froth zone to and into the outlet duct nozzle
- The effect of operating parameters on liquid flow up the riser pipes
- The effect of operating parameters on froth or spray flow across the tray

Operating parameters which were evaluated with this model included:

- Liquid inventory/level in the tank
- Gas flow
- Gas pressure

The goal was to observe, study, and verify the effectiveness of the individual design feature, and to identify any changes, which could improve the performance. Parametric tests were conducted to study the design for each specific feature, as well as at least one alternative design. This allowed determination of at least the qualitative effect of the deviation from the current design.

Nine-module model: The second model incorporated multiple (9) individual KEPAR sieve tray modules. It allowed the study of the interaction of adjacent modules, and specifically allowed the evaluation of the effects of the intersecting downcomer boxes. Because this model was also used to study the tank mixing phenomena, it was constructed with riser pipes and downcomers which were half of the full-scale depth. This allowed for more realistic tank mixing evaluations, without sacrificing the ability to evaluate the hydraulic performance of the two-phase flow above the sieve tray. The configuration of the nine-square model is shown in Figure 7 and 8.

The gas/liquid model study was used to identify any necessary adjustments to the KEPAR design features, including:

- Duct pipe size, number and arrangement
- Riser pipe size, number and arrangement
- Sieve tray open area
- Downcomer configuration
- Weir height

To reduce the number and extent of required model modifications to a minimum, most of the configuration evaluations were achieved by designing into the models the capability for adjustable or easily removable components. For example, the single square model was designed with an adjustable weir. The effect of configuration changes was simulated by blocking off model components to render them inactive for certain tests. This was done in the case of the sieve tray gas holes, riser pipes and duct pipes of the single square model, and for the module-to-module gas layer communication passages for the nine-square model.

5.2 Chemical Performance Model Tests

The second kind of model test conducted as part of the verification was a chemical performance model test. A model very similar to the KEPRI bench scale model was constructed and tested to confirm the previous results of SO_2 removal testing in the KEPRI bench scale and pilot scale models. The design of the chemical performance test model used in the verification is shown in Figures 9 and 10.

Unlike the previous bench scale and pilot plant chemical performance tests, the chemical model tests for this investigation used heated air with controlled injection of SO_2 gas to simulate the flue gas. Variables for the tests included gas flow, initial slurry level, tank pH, absorber differential pressure and inlet SO_2 concentration. A series of air/water tests was also conducted using the chemical test model so that the recirculation rate could be characterized as a function of the operating variables. This was done to allow comparison of the liquid recirculation rates in the 1/8-scale models to that in the chemical performance model.

6. Results and conclusions from Model Testing

Results and conclusions of the model tests conducted for purposes of the verification of the design revisions to the KEPAR are summarized below, in five generic categories.

6.1 Characterization of Two-Phase Flow

Recirculation Rate: The new modular design of the KEPAR lower deck was found to result in significantly lower liquid recirculation rates than those previously derived by KEPRI based on theoretical calculations alone. However, the measured rates, which were approximately 10 liters per Nm^3, were found to be adequate to sustain SO_2 removal efficiency at or above 90 percent when the initial liquid level above the sieve tray was maintained at 150 mm. From this we conclude that the theoretical calculations of KEPRI were not representative of actual conditions during the previous pilot plant or bench scale testing. It should be noted that KEPRI did not attempt to measure liquid recirculation rate in its previous tests, but relied solely on the theoretical calculations.

Gas Layer Formation: At lower loads the model observations indicate that formation of a contiguous gas layer may not be possible. Discrete gas bubbles associated with each duct pipe formed but did not merge. Under these conditions the sieve tray holes in the areas not underlain by gas bubbles were free to provide recirculation of liquid. This means that measured liquid recirculation rates at low loads (which were based on measurements of riser pipe velocity) are likely underestimated in the current study. At low loads (low percentages of full load gas flow) the bubbling action of the gas through the liquid probably becomes more important to maintenance of SO_2 removal than is the case at high loads. The operating flexibility of the current KEPAR design was proven by the fact that SO_2 removal efficiencies of 90 percent could still be maintained provided initial liquid levels above the sieve tray were at 150 mm.

Froth Height and Flow over the Weir: The test results showed that froth levels remained high enough to carry over the weir except at very low initial liquid levels or low gas flows. However, because froth height decays as distance from duct pipe increases, proximity of the duct pipes to the weir is an important design consideration for maximizing recirculation.

6.2 Factors Affecting Liquid Recirculation

Liquid recirculation rate affected primarily by absorber ΔP and liquid inventory in the tank was observed. This confirmed the previous understanding of the mechanism and driving force for control of liquid flow up the riser pipes.

6.3 Factors Affecting SO_2 Removal

The most dominant factor affecting SO_2 removal was found to be the initial level of liquid above the sieve tray. By inference this also means that absorber differential pressure will affect SO_2 removal. However, ΔP itself is dominated by the same influence, namely liquid level above the tray.

6.4 Conclusions Regarding Verification of the Original Design

The original KEPAR design as suggested by KEPRI's changes from its initial design of Youngdong Unit 2 will be adequate to maintain recirculation rates and SO_2 removal over a wide load range. Providing gas communication passage between adjacent modules below the sieve tray for pressure equalization purposes enhanced stability of operation at all loads. Suggestions for design simplification are listed below.

6.5 Future Provisions for Design Simplification

Riser Pipes: Due to the overestimation of liquid recirculation rate at the initial research and test, the number of riser pipes used in its original design of each module could be reduced dramatically without sacrificing performance. A single riser pipe located at the center of each module will be adequate, and will simplify and unclutter the area beneath the sieve tray. This will improve gas layer formation and reduce the risk of chemical scale formation in this area.

Duct Pipes: Test results indicate that acceptable performance from a recirculation rate standpoint could be achieved with a smaller number of larger duct pipes. Provided that the arrangement of the duct pipes properly considers gas/liquid contact and maintenance of froth flow over the weir, configurations utilizing eight duct pipes instead of the 16 indicated by KEPRI should be suitable for full-scale module designs. Elimination of the riser pipes and duct pipes from the current arrangement, as described above, will allow the dimension of the square module to be decreased somewhat from the original KEPRI design of 2.6 meter square.

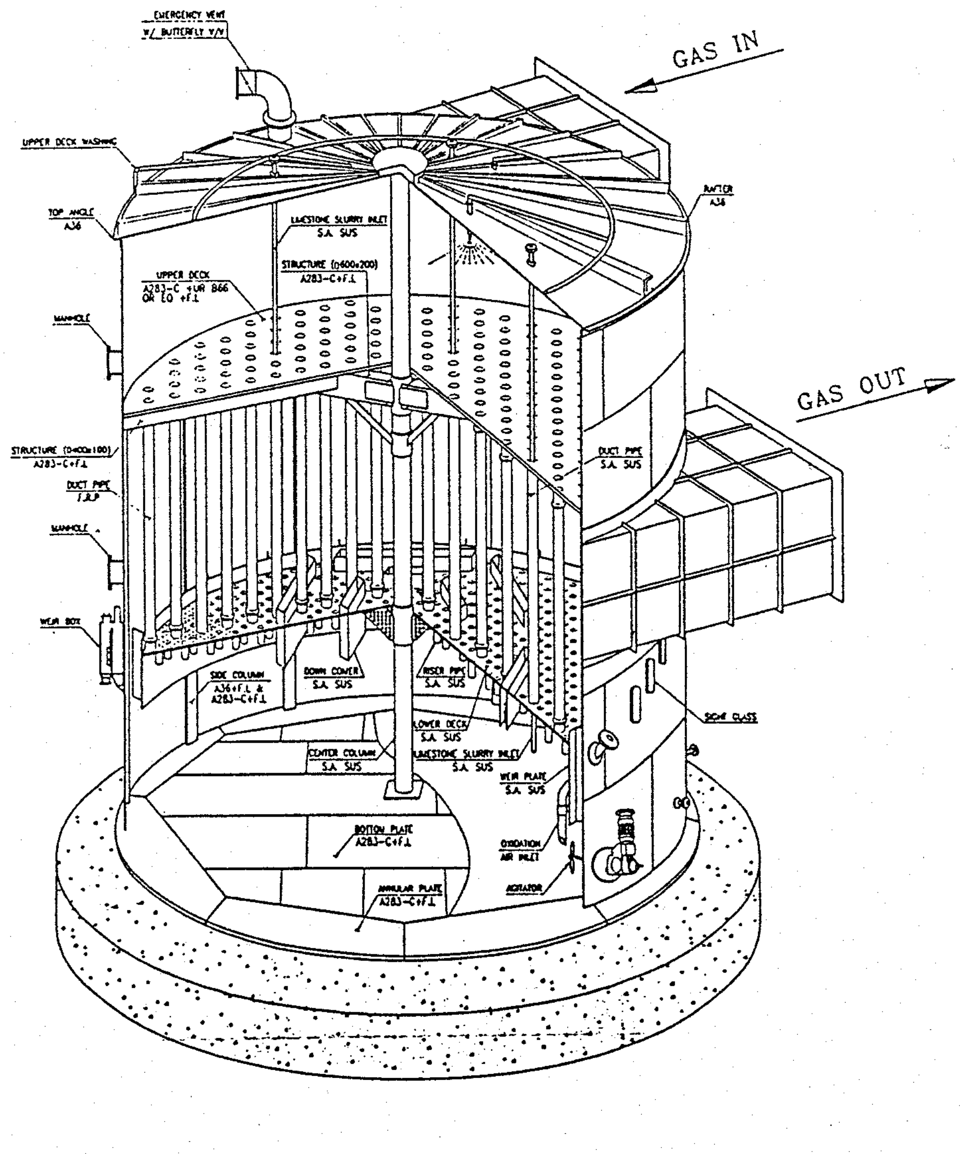

Fig. 1 Basic Concept of the KEPAR

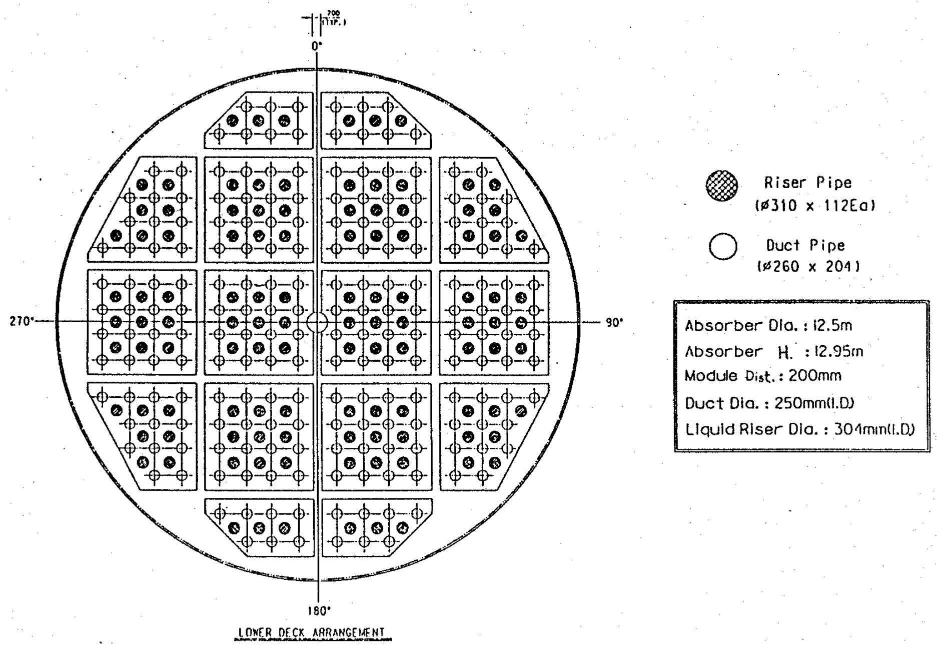

Fig. 2 Lower Deck Arrangement for Young Dong Unit 1

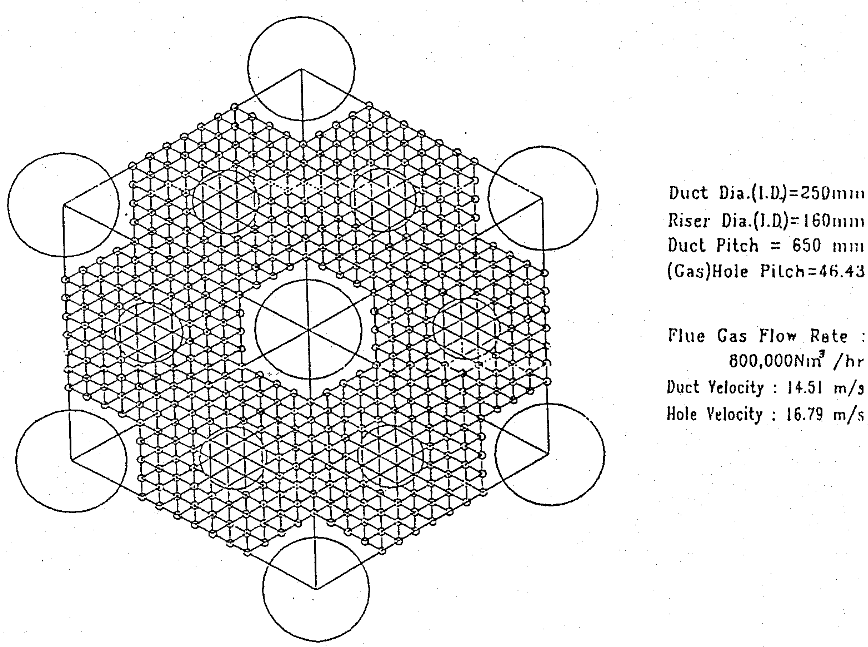

Fig. 3 Honeycomb Arrangement of Sieve Tray

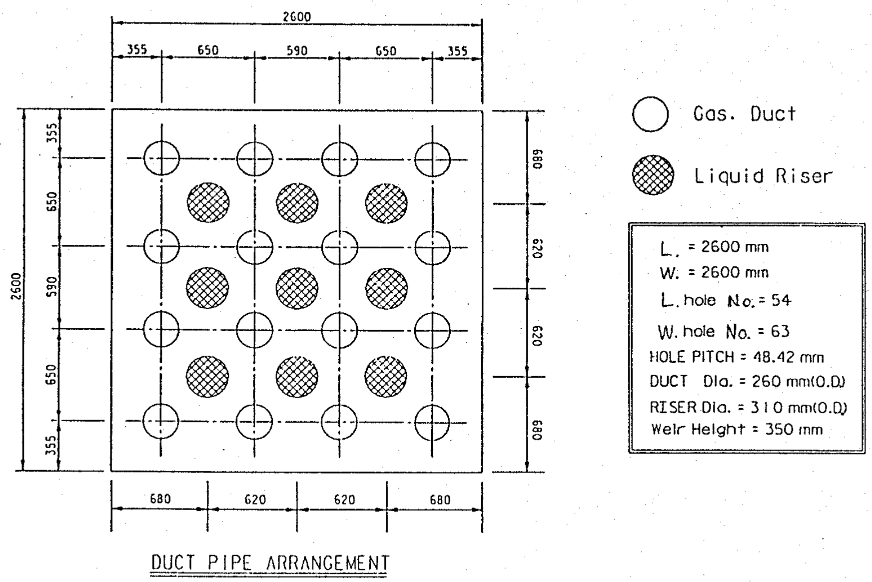

Fig. 4 Rectangular Arrangement of Sieve Tray

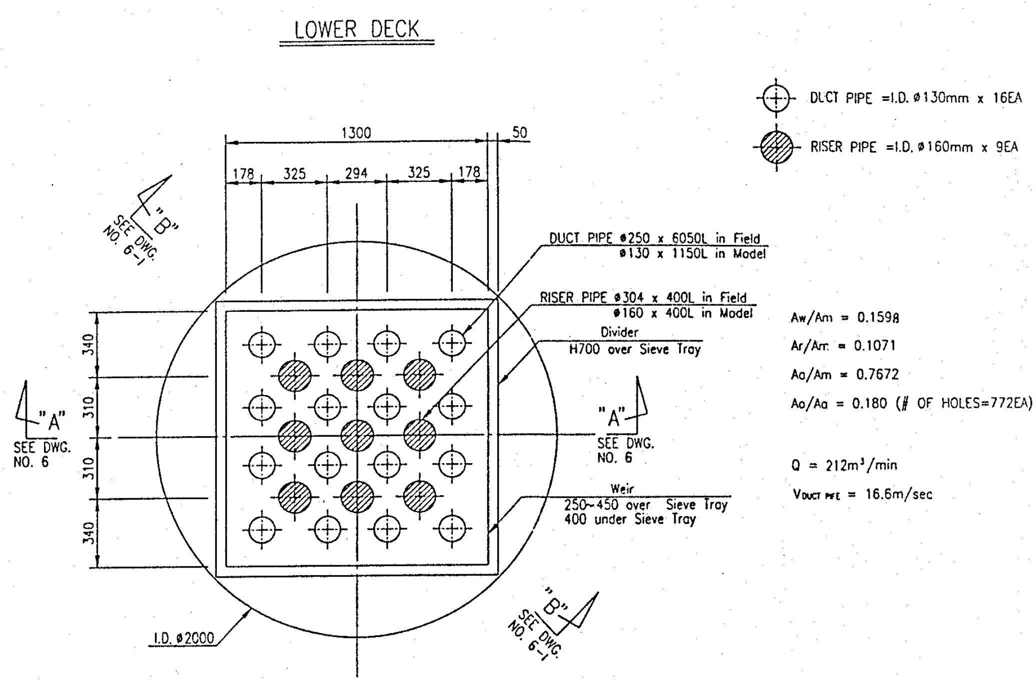

Fig. 5 Configuration of the Single Square Model

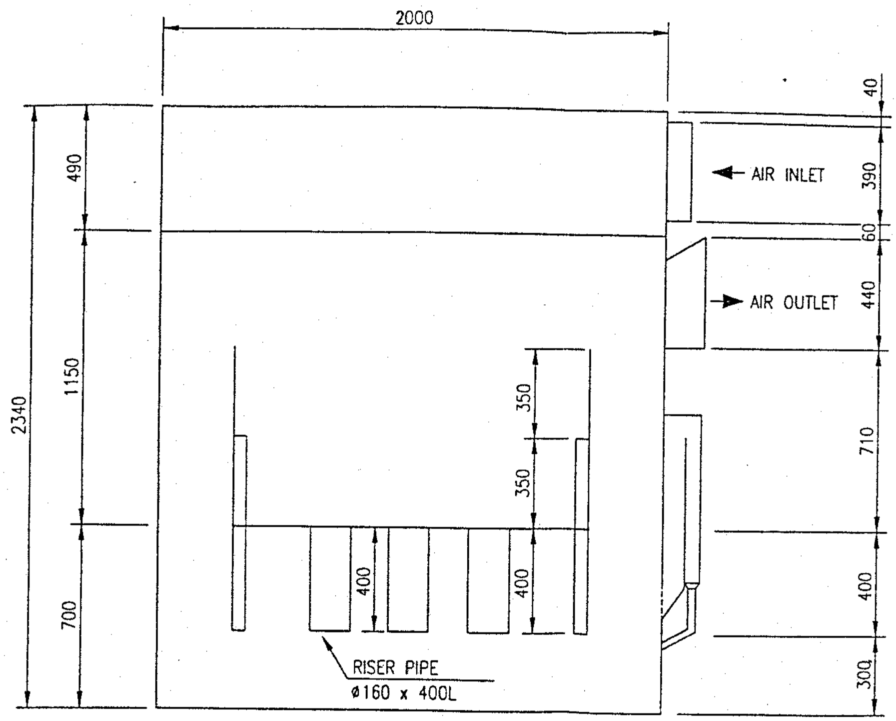

Fig. 6 Configuration of the Single Square Model Profile "A-A"

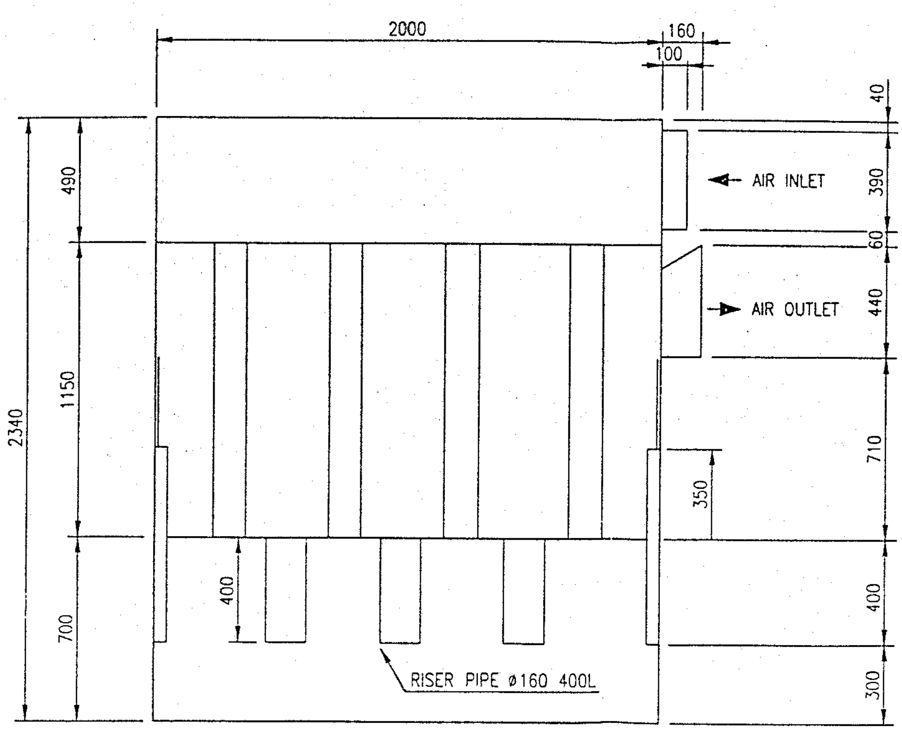

Fig. 6-1 Configuration of the Single Square Model Profile "B-B"

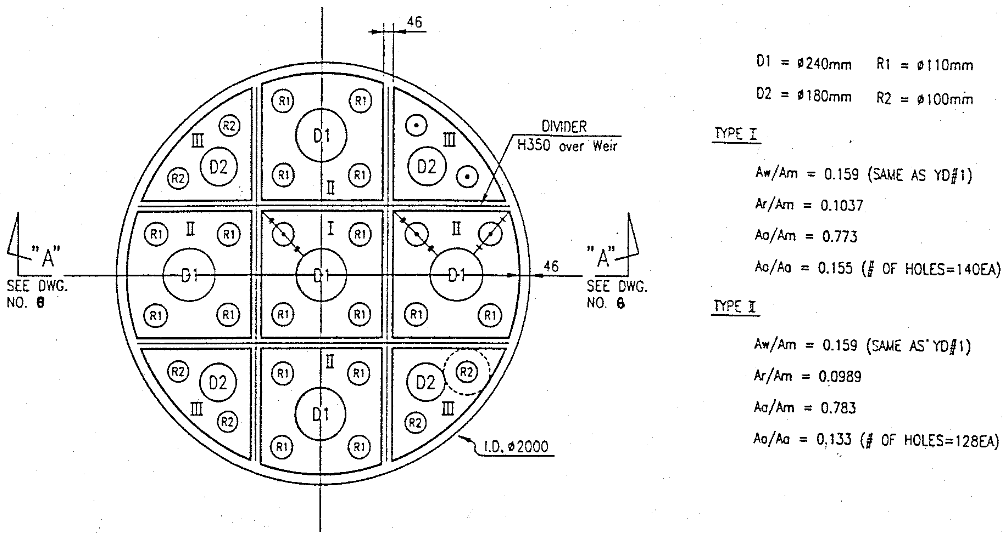

Fig. 7 Configuration of the Nine-Module Model

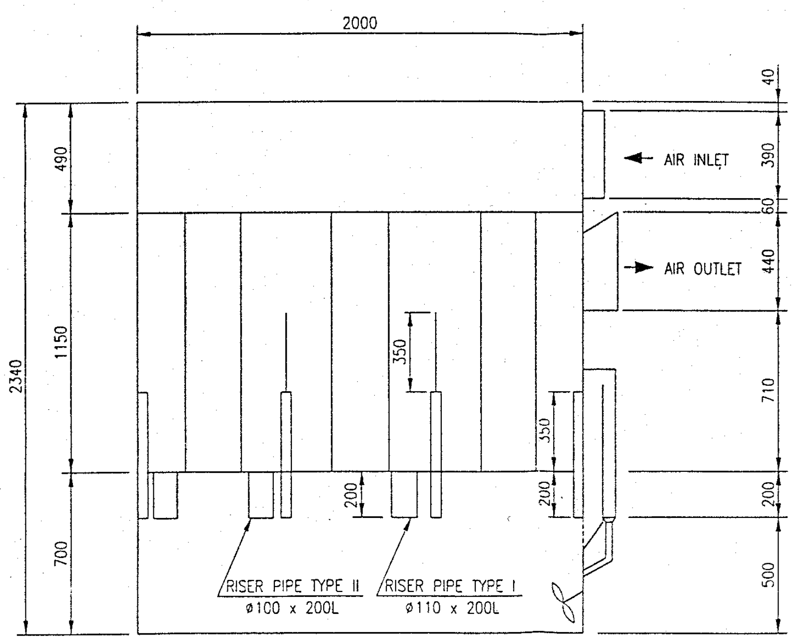

Fig. 8 Configuration of the Nine-Module Model Profile

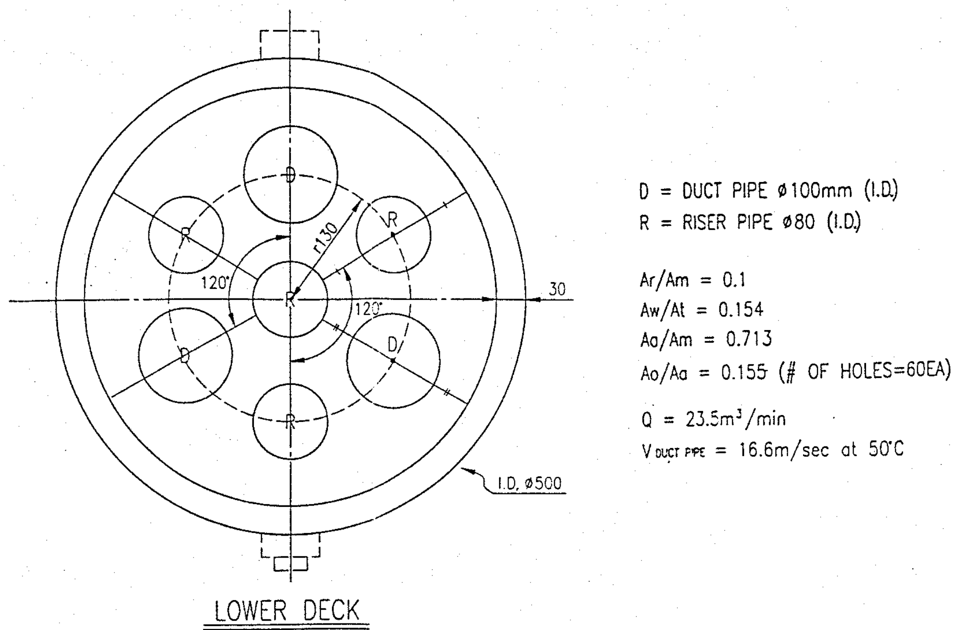

Fig. 9 Configuration of the Chemical Performance Test Model

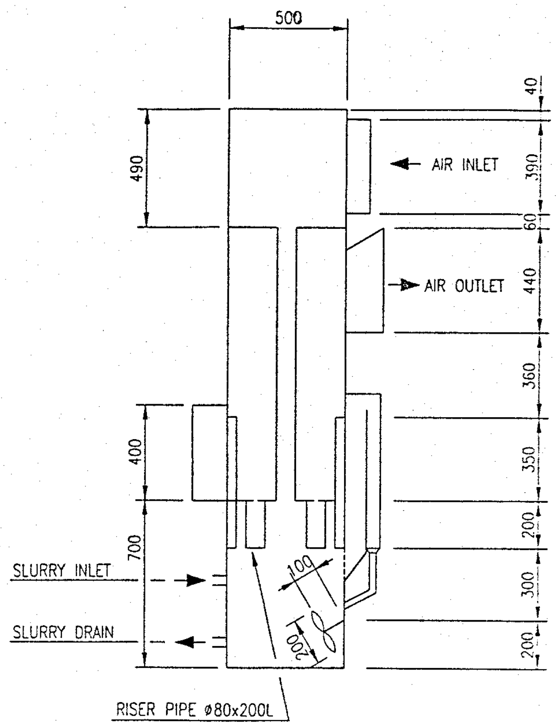

Fig. 10 Configuration of the Chemical Performance Test Model Profile

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