

# PERUPS (PERFORMANCE UPGRADE SYSTEM) FOR ON-LINE PERFORMANCE ANALYSIS OF A NUCLEAR POWER PLANT TURBINE CYCLE

SEONGKUN KIM\* and KWANGHEE CHOI

Department of Mechanical Engineering

Hoseo University

29-1. Sechul-ri, Baebang-myun, Asan, Chungnam, Seoul, Korea, 336-795

\*To whom correspondence should be addressed. kimskun@office.hoseo.ac.kr

*Received August 12, 2004*

*Accepted for Publication December 22, 2004*

---

We developed the PERUPS system to aid the on-line performance analysis for the turbine cycle of the YongGwang 3 and 4 nuclear power plants. Procedure of measurement validation is included in the performance calculation to obtain heat balance. Precision of on-line performance calculation is increased via practical modifications of standard calculation algorithms based on the PTC (Performance Test Code). The proposed system also provides useful Web-based aids for performance analysis, including performance data management, a graphic viewer for heat balance and turbine expansion lines, and synthesized reports of performance.

---

**KEYWORDS :** Turbine Cycle, Measurement Validation, Nuclear Power Plant Performance, Web-based Heat Balance

---

## 1. INTRODUCTION

The degradation of turbine cycle performance has a severe effect on the economy of power plant operation and increases the portion of maintenance and operation costs compared to the total cost of power generation. Higher efficiency for a nuclear power plant can be achieved by using a precise evaluation of turbine cycle performance and by managing cost-effective remedies for the causes of gradual degradation of turbine cycle components.

We developed a Web-based performance analysis system, PERUPS (PERformance UPgrade System), to provide a precise analysis of turbine cycle performance. Systems developed previously for the performance analysis of domestic nuclear power plants were off-line systems that required a off-line acquisition and processing of measurement data to create input data used for performance calculations [1]. In contrast with the off-line system, the PERUPS system was developed to make it possible for consistent performance evaluation using the on-line plant measurement data of the YongGwang 3 and 4 nuclear power plants. The proposed system can provide real-time evaluation of turbine cycle performance using heat balance calculated from the on-line measurement data of the turbine cycle. Validation and verification of the measurement data in the turbine cycle is required for

the use of on-line power plant data. The performance calculation in PERUPS is designed with a step of validation for the measurement data.

For a robust performance analysis for a case in which measurement errors occur, we made several modifications from the ASME (American Society of Mechanical Engineers) PTC (Performance Test Code)[2-5], which is regarded as the industrial standard for performance calculation in most power plants worldwide. The procedures for heat balance evaluation were modified using an approximate model that has mapping relations with the acceptance performance model in accordance with ASME PTC. Acceptance performance refers to the verified performance provided initially by plant vendors after the construction of power plant turbine cycle is completed. We developed an algorithm for the process of verification and validation of the on-line measurement data using a correction model developed from correct measurement data obtained in the early stage of plant operation. Inference models for the correct measurement value are linear models that have independent variables selected from the most correlated variables. A linear regression model is used to develop the inference model using the on-line measurement data sets. Before PERUPS system was developed, the NOPAS (Nuclear Operating Performance Analysis System) system [1] had been developed

as the first attempt for the development of a performance analysis system for a nuclear power plant. The system used plant design data supplied from vendors and plant acceptance data from several domestic nuclear power plants: Kori 1, 2, 3, and 4; Wolsung 1; Uljin 1 and 2; and YongGwang 1 and 2. Because the NOPAS system used data common from several plants, a verification scheme was developed using a virtual plant model [6]. However, the regression model of verification used in PERUPS is based only on the measurement data of the YongGwang 3 and 4 plants in their early stage of operation, and it is regarded as the correct measurement model.

Several systems could be compared to PERUPS, such as PMAX from Scientech. Co. and EtaPro from General Physics Co., among others. The PMAX system provides web-based processing of plant analysis, detecting "lost-megawatts" and optimizing candidates for maintenance. The system can also provide a "What if?" calculation module based on scenarios. The EtaPro system is a PC-based on-line performance analysis system. It has modules for historical trend recovery, a database report writer, on-line controllable parameter diagnostics, and on-line equipment troubleshooting diagnostics. Besides these systems, there are several plant analysis systems, such as the PlantView system of Engineering Consultants Group, Inc., the Fcycle and Ccycle systems of Encotech, Inc., and the Energy Tools system of Computing Technologies International, Inc. However, these systems, including PMAX require a custom process for plant modeling. Users of PERUPS do not require plant modeling, because PERUPS provides customized plant model for domestic nuclear power plants. It also provides a customized on-line connection with the plant computer for acquisition of performance measurement data. Without this customization, users must perform a rigorous correlation between the plant data code and the variables of a commercial system.

The proposed system uses a Web-based interface and has a Web-based DBMS (Data Base Management System) for the management of performance analysis data. The web interface provides users with customized heat balance graphics, turbine-expansion line reports, trend graphs, and automatic generation of analysis reports. We adopted a web-based GUI because it can provide easy access to several plants and a centralized database control to compare the performances of each plant. The system is also simple to install and can be used anywhere in the plant. The system was successfully installed at YongGwang plants 3 and 4, and it is being used now for performance analysis at those locations.

## 2. GENERAL CALCULATION PROCEDURE FOR OPERATING PERFORMANCE OF A TURBINE CYCLE

The turbine cycle of a nuclear power plant is composed of multi flow-trains connection of components, including

a steam generator, a high-pressure turbine, a generator, a reheater, a moisture separator, a low-pressure turbine, a condenser, low pressure feed water heaters, a dearator, high pressure feed water heaters, and pumps, among other components. Each component has generally two or three flow-trains of steam or feed water flows. These components are connected to make a turbine cycle, as shown in Fig. 1. The diagram represents the turbine cycle of the YongGwang 3 and 4 plant units. The diagram describes the turbine cycle by single flow-train structure so that the flows of each flow-train are summed as if there were a single flow-train path. A diagram such as that shown in Fig. 1 is normally called a heat balance diagram of a turbine cycle. The items in the heat balance diagram include flow, temperature, pressure, and enthalpy of important cycle points. Also included are electric output, heat rate, cycle efficiency, as well as the TTD (Terminal Temperature Difference) and the DCATD (Drain Cooler Approach Temperature Difference) of the feed water heaters, moisture separator, and reheater.

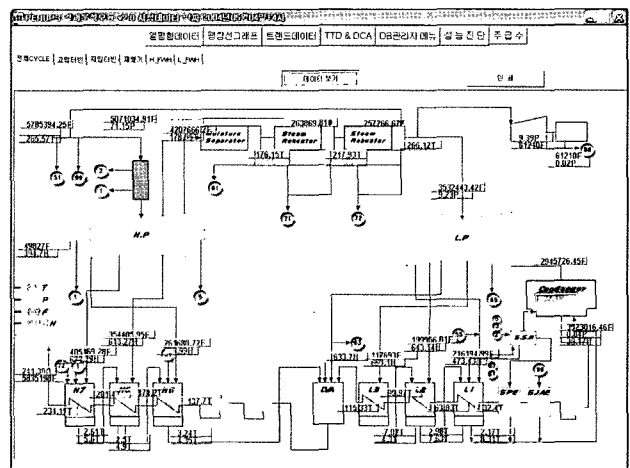


Fig. 1. Turbine Cycle of Nuclear Power Plants YongGwang 3 and 4

The heat balance of a turbine cycle is generally calculated using ASME PTC 6, PTC 6A [2, 3] and the performance test guide of the Korea Electric Power Corporation. Heat balance provides information about the status of flow nodes in the flow network of the turbine cycle. Using mass balance and energy balance, the status of flow rate, temperature, pressure, enthalpy and entropy are determined. Detailed procedures of heat balance calculation are basically iterative procedures. Convergence of the heat balance calculation can be obtained mathematically, using an optimization procedure in which independent variables represent the status of the turbine ELEP (Expansion Line End Point), and the object function to minimize is normally defined as the error of heat balance [7, 8]. The PTC provides general procedures for the recursive convergence of heat balance in which curvature data of the expansion line in the Mollier chart is used for

selecting a new ELEP. Although details of the heat balance calculation cannot be described in this paper, the general principles applied in the PERUPS system can be summarized in the following sequence [9, 10].

Mass and energy balance calculations are applied initially to steam generator inlets and high pressure feed water heater lines using simultaneous linear equations. The pressure, temperature, enthalpy, and flow rate in the high pressure feed water heater train lines are calculated, and the enthalpy of the extracted steam inlet for the feed water heater is determined. Using these values, the flow estimation of the extracted steam from the turbine is obtained. The pressure, temperature, and flow rate in low pressure feed water heater train lines are calculated, and the enthalpy of the extracted steam inlet for the feed water heaters is initially assumed. The flow estimation of the extracted steam in the low pressure turbine is obtained based on these values. Iterative calculation procedures are applied for the enthalpy balance of the drain tank. Stop-valve leakage and turbine gland steam are calculated from the power plant design data of leakage flow coefficients. The moistures of the turbine extraction and exhaust in each turbine stage are calculated using the iterative process of moisture determination during the moisture separating stage. An assumption of dry steam is applied in the initial iteration. New moisture is obtained from the heat balance calculation of extraction nodes. The iteration is repeated until there is a small variation of moisture. The ratio of vent flow and drain flow of the MSR (Moisture Separator) is fixed, as in the plant design data. The initial ELEP enthalpy is assumed using the approximate curvature of the expansion line in the Mollier chart. The estimated new ELEP is re-calculated until the ELEP deviation is less than 0.1 Btu/lbm. If the ELEP deviation is within the range, then the heat balance calculation is completed. Finally, the heat rate, thermal power, and cycle efficiency are calculated from the heat balance data.

### 3. NEW ADAPTATIONS IN PERUPS FOR THE CALCULATION OF OPERATING PERFORMANCE

Robustness in performance calculation needs to be increased to make the calculation reliable even for actual cases in which errors in on-line measurement values occur. Although the basic principles supplied from the ASME PTC cannot be altered, approximate methods can be modified to create new robust procedures to reduce calculation errors. In particular, the enthalpy properties of turbine-extracted steam are very sensitive to mass flow quantities, because the enthalpy value is estimated using the heat balance equation, which includes a mass quantity that has a much larger value relative to that of the enthalpy. This incorrectly estimated value of mass flow has a general tendency to cause mismatch errors in the fitting calculation of the turbine expansion line during

iterative calculations for the turbine cycle heat balance. We made several adaptations in the calculation of operating performance in PERUPS to increase its robustness. These adaptations enabled the performance calculation program of PERUPS to be executed without a run-time error. When misreading measurements were virtually generated within a 10% error of temperature and a 5-10% error of pressure except a few very sensitive measurements points, the calculation in PERUPS can be executed without a run-time error. Although the calculation robustness increased, this performance result could not be verified with a correctness of performance calculation. Users of PERUPS with an input checking user interface would see messages warning of input measurement deviation from the normal range and would be able to understand that although performance results were obtained, the calculation was based on abnormal measurements.

#### 3.1 Enthalpy Distribution in the Feed Water Line

Calculation robustness was increased by a large amount using the assumption of linear enthalpy distribution in high-pressure and low-pressure feed water train lines rather than the linear pressure distribution assumption in the PTC 6. A linear distribution of pressure along the feed water line was previously assumed in the performance calculation, but the distribution of the pressure along the low pressure feed water heater lines of the YongGwang 3 and 4 units was not strictly linear in form. Several verification attempts in the early development stage of the PERUPS system revealed that the assumption of linear pressure distribution could be changed to an assumption of linear enthalpy distribution, to obtain a more accurate calculation.

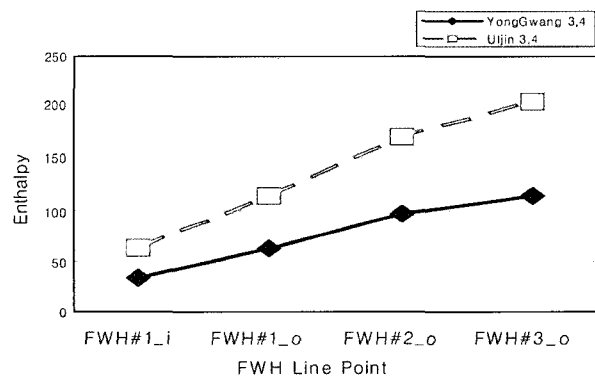


Fig. 2. Enthalpy Distribution of a Steam Inlet in Low Pressure Feed Water Heaters

The calculated data of the feed water enthalpy of the low pressure feed water heater line of the YongGwang 3 unit is shown in Fig. 2. FWH#1\_i means refers to a point of low pressure feed water heater #1 inlet and FWH#1\_o is the point of low pressure feed water heater #1 outlet. The data was based on the acceptance test data. The

distribution in Fig. 2 reveals that there is a fixed ratio between each outlet point of feed water enthalpy in the FWH (Feed Water Heater) line. The Uljin 3 and 4 plants distributions are very similar. We adopted a new estimation formula for the enthalpy of the FWH inlet steam based on these ratios. We examined this estimation formula for several cases of plant acceptance conditions to verify the applicability. The error of the heat balance in feed water heater line was within acceptable range. The enthalpy of the feed water line is estimated using the distribution, and the result is used for the calculation of the inlet steam enthalpy of the feed water heater. This approach reduces the sensitivity of the heat balance calculation related to the incorrect estimation of the steam inlet and the drain flow in the FWH line.

### 3.2 Estimation for Unmeasured Drain Flow and Confluence Flow

Although measurements for the drain flows of the moisture separator (MSR), reheater, high pressure FWH, and low pressure FWH are inevitably required for the heat balance calculation, some nuclear power plants have no measurement devices installed in their drainage flow paths. There are normally about 20 unmeasured points in the drain flows of the YongGwang 3 and 4 units. We assumed that the ratio between the main steam flow and the respective drain flows could be maintained at an approximate constant value for the heat balance estimation. The assumption was effectively applied for the case of the heat balance of the YongGwang 3 and 4 plants. Because there was no measurement history for these drain flows after the initial plant acceptance test, the correctness of the estimation proposed in this paper can not be fully justified. Nevertheless, the application of the estimation of drain flows in PERUPS produced a successful result in the total calculation of the heat balance, and the estimated value was proven to be within a plausible range as determined by experts in the department of power plant operations.

The PTC recommends an exact measurement for the flow rate at the deaerator in/out and for the confluence of the two extracted steams to the low pressure #1 feed water heater. We assumed that an initial heat balance could be used to extract a ratio around the respective flow rates at the deaerator in/out. Using the ratio, we could obtain the heat balance data around the deaerator in 90-100% electric load conditions.

We need an inverse estimation procedure for a confluence case in which two extracted steams from a low-pressure turbine have a confluence junction to an inlet steam flow of the feed water heater. We also assumed that the acceptance heat balance data could be used to extract the ratio between these two inlet flows of the confluence junction. These assumptions were successfully applied and verified in the heat balance calculation for the YongGwang 3 and 4 units.

### 3.3 Moisture Estimation in the Extraction Stage of a Turbine Expansion

The moisture of the extraction point in a turbine cannot be measured, but its value is required to calculate the heat balance around the turbine extraction point. An estimation algorithm for the moisture of the extraction point was developed using an iterative procedure in PERUPS. The algorithm can be described in the following sequence, and the symbols used in the description below are shown in Fig. 3 representing the turbine moisture separation stage.

- 1) Find  $P_s$  (pressure) =  $P_{Si} = P_{So} = P_w = P_{e\_all} / (1 - DPe/100)$ , where  $DPe$  is pressure drop ratio in extraction line
- 2) Determine  $H_{Si}$ (enthalpy),  $S_{Si}$ (entropy),  $M_{Si}$ (moisture)
- 3) Find  $M_{So}$ ,  $H_{So}$ ,  $V_{So}$ (specific volume),  $S_{So}$ , using design data of turbine stage MRE(Moisture Effectiveness)
- 4) Determine  $W_{So}$  from  $M_{So}, V_{So}, P_s$  and design flow coefficient relating stage pressure and outlet flow
- 5) Calculate  $W_e$  from  $W_{Si}$  and  $W_{So}$
- 6) Find  $W_w$  from  $W_{Si}, M_{Si}, M_{So}$  and  $H_w$  from  $P_w$
- 7) Find  $He\_all = (W_{Si} * H_{Si} - W_{So} * H_{So}) / W_{e\_all}$

Subscripts are used to represent "s" for stage, "i" for inlet position, "o" for outlet position, "e" for extracted steam, "w" for separated water and "e\_all" for the confluence into the extraction line to the feed water inlet. The iterative sequence from steps 1) to 7) is applied until the deviation of the moisture of the extracted steam is within specified range.

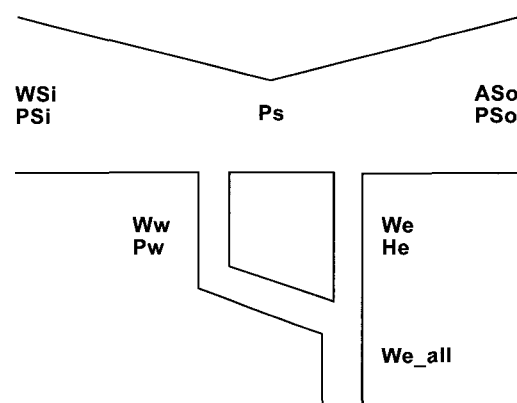


Fig. 3. Moisture Separation Stage in the Turbine Expansion

According to the types and the design specifications of extraction stages in turbines, slight modifications have been made to the procedures of the algorithm. Results of the estimation could be verified by the enthalpy value of extracted turbine steam. The estimation was verified by comparing the enthalpy values of the accepted heat balance of the YongGwang 3 and 4 units.

### 3.4 Comparison of Heat Balance Calculations

Based on the adaptations in this section, a heat balance calculation procedure was developed and the comparative results of PERUPS with the accepted heat balance from the manufacturer are shown in Table 1. The symbols in

Table 1 are the symbols used in PERUPS to abbreviate a description of a status point. Heat balance was compared for the same condition as in plant acceptance stage. As shown in the table, the deviations in the heat balance were within the range of validity for practical purposes.

**Table 1.** Comparison of Heat Balance Calculation Results

Symbol	Description	Acceptance: Manufacturer's Data	PERUPS: Calculated Data	Unit
WEht_1	HP #1 Ext. Steam Flow to FWH	404061	404018	kg/h
WEht_2	HP #2 Ext. Steam Flow to FWH	353277	353261	kg/h
WEr1_j	1st Reheater Inlet Heating STM Flow	263027	263107	kg/h
HSlt_i	LP Turbine Inlet Steam Enthalpy	714.366	714.4	kcal/kg
HElt_1	LP #1 Ext. Steam Enthalpy to FWH	665.162	665	kcal/kg
HElt_2	LP #2 Ext. Steam Enthalpy to FWH	643.925	641.5	kcal/kg
ELEPit	LP Turbine ELEP	539.008	539.1	kcal/kg
UEEPit	LP Turbine UEEP	548.266	548.4	kcal/kg
NHRcy	Turbine Cycle Net Heat Rate	2315.6	2315.2	kcal/kWh
GHRcy	Turbine Cycle Gross Heat Rate	2315.6	2315.2	kcal/kWh

## 4. CALCULATION OF CORRECTION FACTORS

Correction factors are required because current operating condition cannot be same with the condition of plant acceptance stage. The corrective heat balances of group #1 and group #2 are calculated for the comparative analysis of thermal performance as described in the ASME PTC [2, 3]. In the group #1 correction, equipment conditions except for the turbine are assumed to be the same as in the initial design condition of the power plant, and the heat balance is re-calculated using these conditions. Correction factors for group #1 include factors that have effects on the heat rate via the condenser and the feed water heaters to isolate performance deviations caused only by the turbine and the generator. In the group #2 correction, the cycle efficiency and the heat rate are corrected for variables that have direct effects on the turbine cycle. Major correction variables include the TTD and the DCATD of the feed water heater, pressure drop, main feed water pump turbine status, condenser sub-cooling, condenser make-up, power factor, H2 pressure of the turbine, steam generator blow down, condenser pressure, stop valve moisture and pressure, and thermal output.

It is suggested in PTC 6.1 - 1984 that we can use correction curves when it is impossible to calculate exactly the amount to be corrected [2]. In the case of the Yong Gwang 3 and 4 plants, factors from the steam jet air ejector are excluded, because of its relatively minor effects.

The list of group #1 correction factors is as follows:

- Heater #7 TTD Correction Factor
- Heater #7 DCATD Correction Factor
- Heater #7 Extraction Line Pressure Drop Correction Factor
- Feed water Pump Enthalpy Rise Correction Factor
- Feed water Pump Turbine Steam Flow Correction Factor
- Condenser Sub cooling Correction Factor
- Steam Generator Blow down Makeup Correction Factor

The correction factors of group #2 are used to estimate the actual performance of the turbine and the generator when operating conditions differ from those of the design data. We exclude the correction factors for the MSR (Moisture Remover), because MSR can be regarded as part of the turbine/generator. The list of group #2 correction factors is as follows:

- Throttle Pressure Correction Factor
- Throttle Moisture Correction Factor
- LP Turbine Exhaust Pressure Correction Factor

Besides this group of correction factors, a thermal correction factor for electric power must be incorporated into the total correction factor. The heat rate must be corrected if the heat balance is not calculated in thermal output of 100% correctly. The performance test must be corrected against the throttle conditions of the governor valve, because the test point is located between the third valve position and the fourth valve position in the Yong

Gwang 3 and 4 plants.

An example of a heat-rate correction factor for a feed water pump enthalpy rise (CRISE) is described below, and plant symbols for the YongGwang 3 and 4 units are used to designate measurement items for each train:

1) Input feed water enthalpy (Hin) generated from Tin and Pin

• Input feed water average temperature.  

$$(T_{in}) T_{in} = (TW117 + TW118)/2 \quad (1)$$

Where, TW117 is measurement of input feed water temperature of train #1,

TW118 is measurement of input feed water temperature of train #2.

• Input feed water average pressure (Pin)  

$$P_{in} = (FWP0031 + FWP0032)/2 \quad (2)$$

Where, FWP0031 is measurement of input feed water pressure of train #1,

FWP0032 is measurement of input feed water pressure of train #2.

2) Output feed water enthalpy (Hout)

• Output feed water average temperature (Tout)  

$$T_{out} = (FWT0047 + FWT0048)/2 \quad (3)$$

Where, FWT0047 is measurement of output feed water temperature of train #1,

FWT0048 is measurement of output feed water temperature of train #2.

• Output feed water average pressure (Pout)  

$$P_{out} = (FWP0039 + FWP0040)/2 \quad (4)$$

Where, FWP0039 is measurement of output feed water pressure of train #1,

FWP0040 is measurement of output feed water pressure of train #2.

3) Feed water pump enthalpy rise ( $\Delta H$ )

$$\Delta H = H_{out} - H_{in} \quad (5)$$

4) Feed water pump enthalpy rise load correction factor (CRISE LOAD) that correspond to VWO % in correction curve

$$CRISE\_LOAD = 1 + (KW\%\_CORRECTION) \times (\nabla H - \nabla H_{design}) / 100 \quad (6)$$

5) Feed water pump enthalpy rise heat rate correction factor (CRISE HR) that correspond to VWO % in correction curve

$$CRISE\_HR = 1 + (HR\%\_CORRECTION) \times (\nabla H - \nabla H_{design}) / 100 \quad (7)$$

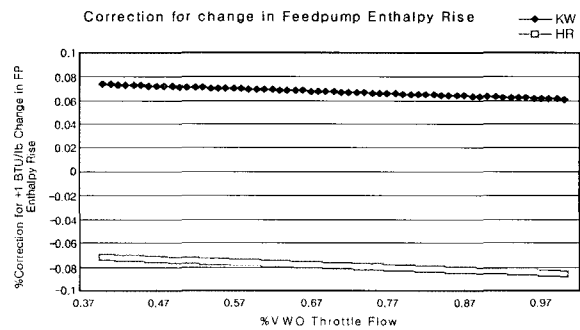


Fig. 4. Correction Curve for the Feed Water Pump Enthalpy Rise for Load and Heat Rate

The correction curves used in 4) and 5) are based on vendor data and are shown in Fig. 4. Normally, the correction curves for electric output and heat rate are

Table 2. Comparison of Correction Factors

List of Correction Factor	PERUPS Calculation Result	Vendor Calculation Result	Corrected Load Difference(MW)
Heater #7 TTD	0.99999	0.999995	-0.00438
Heater #7 DCATD	1.000073	1.000073	0.0
Heater #7 Extraction Line Pressure Drop	1.000675	1.00067	0.005178
Feed water Pump Turbine Steam Flow	1.00174	1.00174	0.00014
Condenser Subcooling	1.000015	1.000015	0.000213
Steam Generator Blowdown Makeup	1.000501	1.000501	0.0000209
Feed water Pump Enthalpy Rise	1.002938	1.002934	0.004273
Throttle Pressure	0.99707	0.997078	-0.00773
Throttle Moisture	1.000411	1.000422	-0.01083
LP Turbine Exhaust Pressure	0.994756	0.994755	0.000454
Electric MW Thermal Correction Factor	1.009761	1.009587	0.176271
Throttling Correction Factor	1.003471	1.003427	0.045548
Total Correction Load	1.011389	1.011184	0.208693

represented in a symmetric format. The curve in Fig. 4 is described as being used internally in PERUPS. The result of the correction factors in PERUPS was compared with the vendor-supplied calculation results, and the comparison result is shown in Table 2. As shown in the table, differences in corrected electric power are small enough to be used for a reliable correction of performance. Correction factors developed in PERUPS are practical approximations for the vendor-supplied correction curve to correct discrepancies of measurement input between the conventional correction curve and the PERUPS inputs. Table 2 represents a comparison between a vendor-supplied correction curve and correction factors in PERUPS.

#### 4. PERFORMANCE DATA VALIDATION

##### 4.1 Validation of Main Feed Water Flow

Calibrations and validations for measurement sensors used in on-line performance analysis are required for a precise evaluation of performance. There are many causes for the collection of invalid performance measurement data, including malfunction or bias of sensors. As a physical example, the fouling of venturi surface in a flow rate sensor increases because of chemical reactions and deposits. We have developed a validation scheme for the correction of measurement data, and we describe our approach in this section, using a main feed water flow example.

A nuclear power plant's operating limit is directly related to its thermal power production. The simplified energy balance equation can be written as [11]:

$$Q_c = mfw * (h_s - h_{fw}) + Losses \tag{8}$$

where  $Q_c$  is thermal power,  $h_s$  and  $h_{fw}$  are the enthalpies of steam and feed water, respectively, and  $mfw$  is the feed water flow rate. Uncertainties in thermal power estimation often come from feed-water flow rate measurements. The majority of nuclear power plants use venturi meters to measure the feed water flow rate. However, these meters are susceptible to measurement drift due to corrosion by the feed water building up on the meter's orifice. This corrosion increases the measured pressure drop across the meters, which results in an overestimation of the flow rate. Consequently, the reactor's thermal power is also overestimated, and to stay within regulatory limits, reactor operators are forced to derate their plants. On average, a derating is between 1% and 2% of full power. The best solution to this problem would be to have an inferential sensing system that can accurately predict feed water flow [12].

The development of an inferential sensing system involves collecting and preprocessing the measurement data to allow the use of statistical signal evaluation techniques. Once the data is collected and preprocessed, an inferential model is developed and tested. Several

predictive modeling techniques can be applied to inferential sensing, including linear techniques, such as regression, principal component regression, ridge regression, and partial least squares [12]; and non-linear techniques, such as non-linear regression, non-linear partial least squares, and artificial neural networks.

Our aim was to create an inference model by which acceptance data and operation data in the initial stage could provide correlation information between measurement data. These data could also be used as sample sets of the estimation model for a correct estimation model of the main flow rate data. The relation can be practically modeled using a regression model based on the sample data without a loss of precision. Most correlated variables are selected using a Pearson product-moment correlation coefficient [13]. The estimation model is formed using linear regression modeling as in Eq. (2). The independent variables are the 6 terms of three measurements of most correlated variables and the three cross products of these variables.

$$y(x_1, x_2, x_3) = \Phi(x_1, x_2, x_3)^T \theta \tag{9}$$

It is important to distinguish the source of bias between the feed-water flow meter and the input variables of the regression model. The input variable has its own regression model used to estimate the input variable. Using these estimation results, a user can obtain information to distinguish the cause of bias.

Table 3 shows the estimation results using the correlated variables and the correct heat balance data. FWFQ1112 represents the main feed water flow in train #1. The maximum value of the estimation error was less than 0.5%, which validated the estimation model as useful.

**Table 3.** Estimation Results for Main Feed Water Flow Rate

Measured FWFQ1112	Estimated FWFQ1112	Estimation Error(%)
2920000	2926402	-0.34
2930000	2930091	0.34
2910000	2918764	-0.34
2940000	2935714	0.34
2950000	2939333	0.33
2910000	2906778	0.34
2930000	2919493	0.34
2930000	2930091	0.34
2930000	2929033	0.68
2940000	2930979	0.34
2900000	2898788	0.34
2920000	2922202	-0.34
2920000	2914234	0.34

Fig. 5 Shows the Web-based GUI in PERUPS for

the general trends of the main-feed water flow and its correlated variables. Using this trend, operators of a power plant can evaluate consistency between these variables. If there is an inconsistent trend among these variables, an operator can infer a malfunction in the main feed water measurement.

The estimation result for the main feed water flow using correlated variables is shown in Fig. 6. In the initial stage of a power plant operation, the assumption of a small drift in main-feed water measurement can be justified. There was small gap between the estimation and measurement at this stage. At the stage of current operation, there is a larger gap between the estimation and measurement of the main-feed water flow. The gap can be regarded as the measurement uncertainty value of

the main-feed water flow. The vertical axes in Figs. 5 and 6 represent scaled values by which to identify the tendency of deviation; the horizontal axes are periodical specified time marks for performance analysis.

### 5. WEB REPORTS IN PERUPS

Fig. 7 shows the Web interface for heat balance result reports. The heat balance information in Fig. 7 includes flow rate, pressure, temperature, and enthalpy of the major points of the flow network. The tables below the heat balance diagrams represent the comparison between current performance data and acceptance performance data. A summary of the turbine cycle heat balance is provided and a sub-section of the heat balance is displayed. These sub-sections include a high-pressure turbine section, a low-pressure turbine section, a MSR-

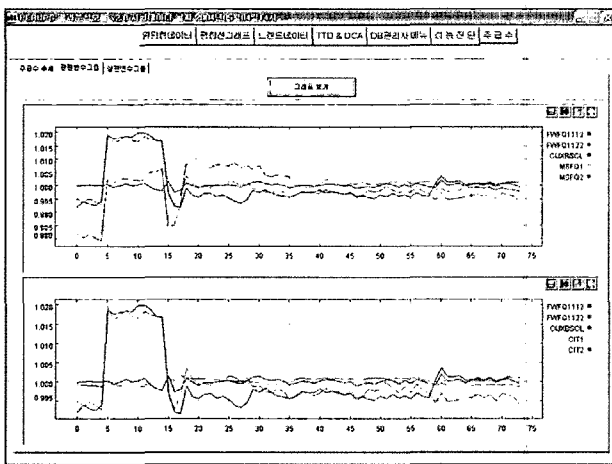


Fig. 5. General Trends of the Main-feed Water Flow and its Correlated Variables

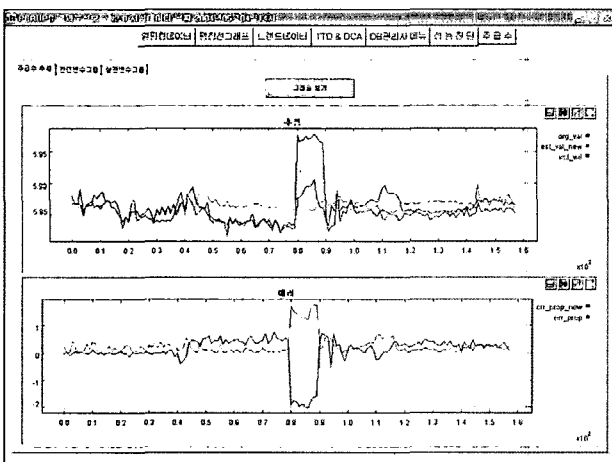


Fig. 6. Estimation for the Main Feed Water Flow Using Correlated Variables

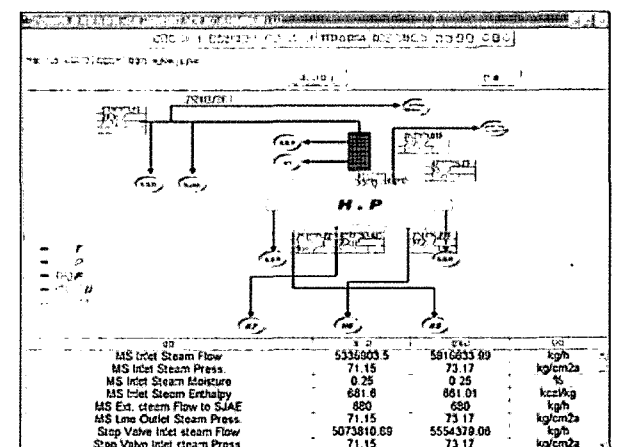
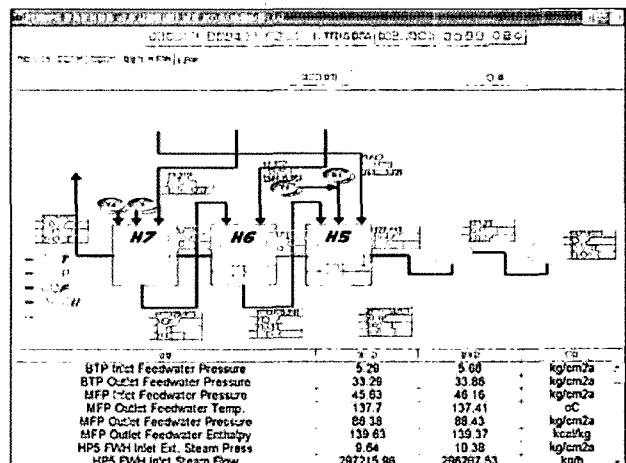


Fig. 7. Web-based PERUPS Heat Balance Output Module



Reheater section, an extraction line section, a condenser and low-pressure feed water heater section, and a high-pressure feed water heater and S/G section. Figure 8 and Fig. 9 show major analysis outputs after performance calculations. The turbine-expansion line report of Fig. 8 shows the change of the turbine state from its acceptance stage. In addition, the turbine expansion line represents core information about moisture separation and turbine efficiency. The trend report of Fig. 9 provides trend data with graphic summary information. A user can customize the spreadsheet-based web report of the performance analysis, and all the results of the performance analysis can be automatically summarized in a spreadsheet report file.

## 6. CONCLUSION

We developed a Web-based performance analysis system, PERUPS, to provide a more precise performance analysis of domestic nuclear power plants. Systems previously developed for performance analysis were off-line systems that required acquisition and processing of the measurement data to create input data used for performance calculations. The PERUPS system was developed to make it possible for consistent performance evaluation by using the on-line plant measurement data of the YongGwang 3 and 4 nuclear power plants. The proposed system can provide a precise evaluation of turbine cycle performance using the heat balance and performances of each component of the turbine cycle. Validation is required for the use of on-line plant measurement data of the turbine cycle. The performance calculation in PERUPS is designed with the validation for measurement data. The general procedures of current performance codes are modified in several ways and are successfully applied to the YongGwang 3 and 4 nuclear power plant cases. In addition to performance calculation, the PERUPS system provides a web-based graphic heat balance, a turbine expansion line, and a customized report. We have found that the proposed system is more practical, and it provides a more reliable performance analysis for domestic nuclear power plants.

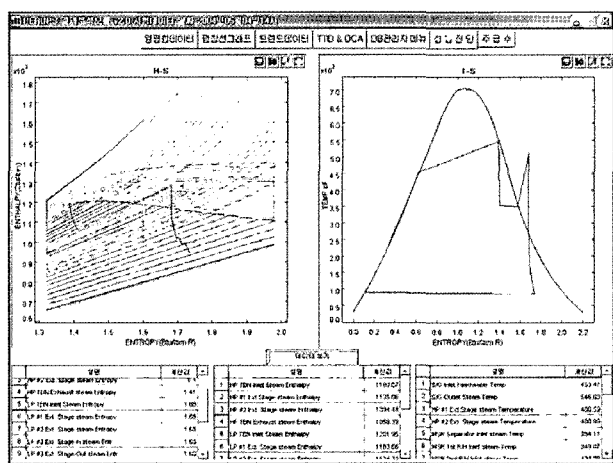


Fig. 8. Web-based PERUPS Output Module of an Expansion Line Report

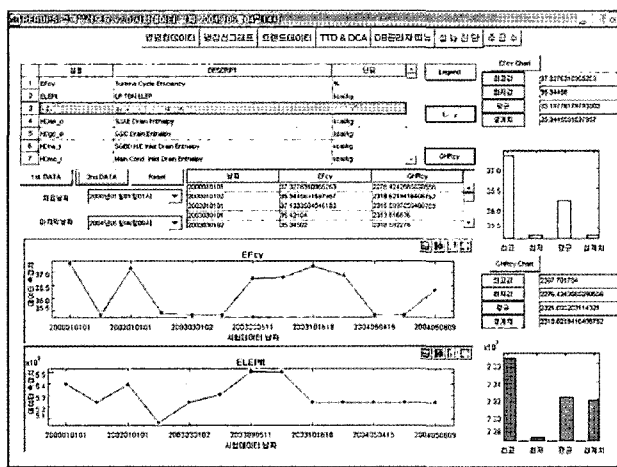


Fig. 9. Web-based PERUPS Output Module of a Trend Report

## Acknowledgements

The authors thank KHNP and KEPRI for their financial support and thank the performance managers at the Yong Gwang nuclear power plants for their help in analyzing the performance results and heat balance data.

## REFERENCES

- [ 1 ] Kim, S.K., and Choi, K.H., "Development of Performance Analysis System (NOPAS) for Turbine Cycle of Nuclear Power Plant", *Journal of Korean Nuclear Society*, Vol. 33-1, pp.34-45, (2001)
- [ 2 ] American Society of Mechanical Engineers Performance Test Code 6, "Steam Turbines", ASME (1976)
- [ 3 ] American Society of Mechanical Engineers Performance Test Code 6A, "Appendix A to Test Code for Steam Turbines", ASME (1982)
- [ 4 ] American Society of Mechanical Engineers Performance Test Code 12.1, "Closed Feed water Heaters", ASME (1978)
- [ 5 ] American Society of Mechanical Engineers Performance Test Code 12.2, "Steam Condensing Apparatus", ASME (1983)
- [ 6 ] Kim, S.K., and Choi, K.H., "Thermal Performance Analysis System Based on Measurement Validation for Nuclear Power Plant", 4th *JSME-KSME Thermal Engineering Conference*, 4, pp.185-190, (2000)
- [ 7 ] British Electricity International, "Modern Power Station Practice: Volume G Station Operation and Maintenance", British Electricity International (1991)

- [ 8 ] Kim, S.K., and Han, S.T., "A Study on the Computerization of Performance Evaluation for Thermal Power Plant", *3rd KSME-JSME Thermal Engineering Conference*, **3**, pp.401-406, (1996)
- [ 9 ] Munchausen, J.H., "EPRI Performance Enhancement Program", *Proceedings of the American Power Conference*, pp. 519-521 (1995)
- [10] Spencer, R.C., Cotton, K.C., Cannon, C.N., "A Method for Predicting the Performance of Steam Turbine-Generators, 16,500KW and Larger", *General Electric Co. Report* (1974)
- [11] Chan, A.M.C., Ahluwalia, A.K., "Feedwater flow measurement in U.S. nuclear power generation stations", EPRI TR-101388, Electric Power Research Institute, Nov. 1992.
- [12] EPRI, "Feedwater Flow Measurement in U.S. Nuclear Power Generation Stations", EPRI (1992)
- [13] Draper, N.R., Smith, H., "Applied Regression Analysis", 2nd Ed. John Wiley & Sons (1976)