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Development of Performance Analysis System (NOPAS) for Turbine Cycle of Nuclear Power Plant

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Abstract

We have needs to develop a performance analysis system that can be used in domestic nuclear power plants to determine performance status of turbine cycle. We developed new NOPAS system to aid performance analysis of turbine cycle. Procedures of performance calculation are improved using several adaptations from standard calculation algorithms based on ASME (American Society of Mechanical Engineers) PTC (Performance Test Code). Robustness in the performance analysis is increased by verification & validation scheme for measured input data. The system also provides useful aids for performance analysis such as graphic heat balance of turbine cycle and components, turbine expansion lines, automatic generation of analysis reports.

Key Words : measurement validation, correlation model, nuclear power plant performance

1. Introduction

As operation of power plant continues, performance characteristics of power plant equipments are degraded by mechanical and chemical causes. The degradation of performance has severe effect on economy of power plant operation because portion of maintenance and operation in total cost is increased. Improvement of plant performance has direct effect on economy of plant operation. The improvement in availability and efficiency of operating power plants can be achieved by precise evaluation of plant performance and economic management for causes of plant degradation.

We developed a computerized performance analysis system, Windows-based NOPAS (Nuclear Operation Performance Analysis System for turbine cycle) to provide more robust performance analysis. This system enables consistent performance evaluation of domestic nuclear power plants. The system can provide precise evaluation of turbine cycle performance in the perspective of plant heat balance and performances of each components of turbine cycle. Performance evaluation is based on verification and validation of turbine cycle measurement data. Also, it provides performance analysis for most of equipments in power plant such as turbine, moisture separator, condenser, high pressure FWH (Feed Water Heater) and low pressure FWH and pumps, etc. We developed our unique model of flow network including almost all of nuclear power plants in Korea. As equipments in domestic power plant were supplied from various vendors, we developed modified routines for performance calculation integrating these various aspects of domestic power plant supplied from different vendors.

Generally, procedures for performance evaluation of nuclear power plant turbine cycle should be developed in accordance with ASME PTC [1-4]. Procedures of turbine cycle performance analysis system developed previously are based on procedures of ASME PTC [5-6]. But, we need some modifications to these procedures and critical problem in the performance analysis is verification and validation of about 80 ~ 200 measurements such as temperature, pressure, flow rate, power output and level, etc. We developed algorithm for the process of verification and validation. Estimation models for the correct measurement value are developed using correlation and regression model [11]. The regression is based on initial plant design data supplied from vendors, plant acceptance data and verified plant performance data of domestic nuclear power plant. We used data set of 9 nuclear power plant units of Kori 1,2,3,4, Wolsung 1, Uljin 1,2 and YoungKwang 1,2 power plant unit.

The system is constructed in a graphic-oriented user interface and has DBMS (Data Base Management System) for management of performance analysis data. It provides download connections with on-line measurements stored in plant computer. It has been installed in the majority of domestic nuclear power plant. It is now used in about 9 nuclear power plants in Kori 1,2,3,4, Uljin 1,2, Wolsung 1, and Youngkwang 1,2 power plant unit. Major functions of the system are as follows,

- Database for performance analysis data and design data of turbine cycle and components
- Verification and validation of measurement data
- User customized unit system
- User customized heat balance graphic of turbine cycle and components
- Turbine expansion line report
- Trend graph for performance index of components
- Performance of turbine cycle, components and thermal output report
- Automatic generation of performance analysis report in user-defined form
- Management of correction curve used in correction calculation
- Download connection to plant computer data

Performance analysis result can be used to cause-effect analysis for degradation factors of plant performance and economic analysis for maintenance candidates. We will describe technical improvements and methodologies implemented in NOPAS system.

2. Operating Performance Calculation of Turbine Cycle

Turbine cycle of nuclear power plant is composed of turbine, generator, moisture separator, condenser, feed water heater and pumps, etc. Fig. 1 represents schematic diagram of turbine cycle of Kori #3 unit.

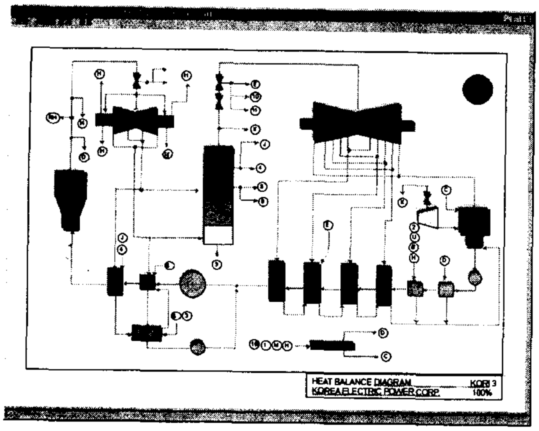

Fig. 1. Turbine Cycle of Nuclear Power Plant Kori #3 Unit

Components of performance analysis in NOPAS system are represented in Fig. 2. Heat balance of turbine cycle is obtained using ASME PTC 6, PTC 6A and performance test guide of Korea Electric Power Corporation.

Heat balance result provides status of flow nodes in flow network of turbine cycle. Using mass balance and energy balance, status value of flow rate, temperature, pressure, enthalpy and entropy is determined. Convergence of heat balance can be obtained using optimization procedure in which independent variables are status of turbine expansion line end point and object function to minimize is error of energy balance. [9] PTC provides approximation method of convergence using curvature of expansion line in Mollier [1] chart.

General procedures of performance analysis based on ASME PTC for turbine cycle can be described by following sequences and summarized in Fig. 3.

1) Preliminary heat balance is calculated with measured data of turbine cycle. Mass balance and energy balance are applied to steam generator inlets and high pressure feed water heater line using simultaneous linear equations. Pressure, temperature, enthalpy and flow status of high pressure feed water heater line is calculated and enthalpy of extracted steam inlet for feed water heater is determined. Using these values, flow estimation of extracted steam is obtained.
2) Pressure, temperature and flow status of low pressure feed water heater line is calculated and enthalpies of extracted steam inlet for

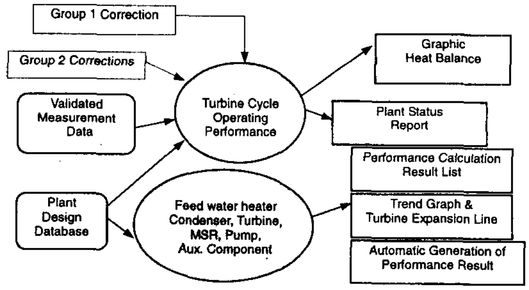

Fig. 2. Components and Procedures of Operation Performance Analysis of Turbine Cycle

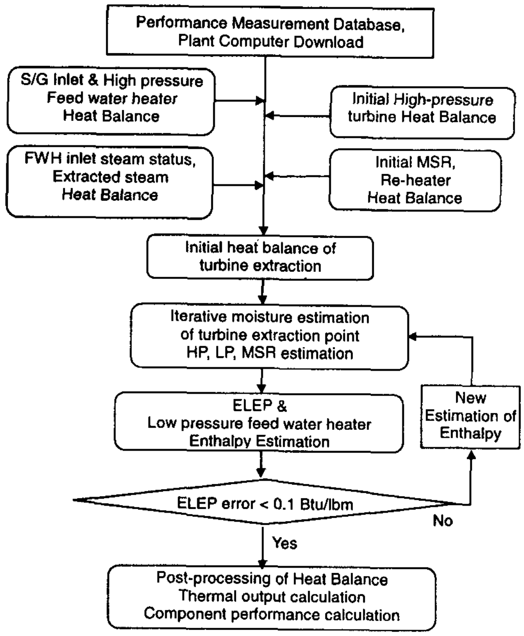

Fig. 3. Calculation Procedure of Operation Performance for Turbine Cycle

feed water heaters are assumed. Using these values, flow estimation of extracted steam is obtained. Some iterative calculation is applied for drain tank.

3) Status of GSC (Gland Steam Condenser) is calculated from status of extracted steam from SSR (Steam Seal Regulator) and turbine gland. Steam flow of SJAE (Steam Jet Air Ejector) is calculated from heat load of SJAE. Extracted steam flow to SSR is also calculated from heat balance result.
4) Status of main steam line is determined from outlet status of steam generator. Status of stop-valve leakage and turbine gland steam are calculated using leakage flow coefficients from design data. Status of turbine exhaust steam is calculated using iterative process of moisture determination of moisture separator stage and exhaust stage. Assumption of dry steam is applied in initial iteration. New moisture is obtained from heat balance calculation of extraction nodes. Iteration is repeated until there is small variation of moisture. Status of MSR (Moisture Separator) and re-heater is calculated from status of extracted steam. Ratio of vent flow and drain flow is fixed as in plant design data.
5) Assume ELEP (Expansion Line End Point) enthalpy using the approximate curvature in the Mollier chart. Calculate heat balance of feed water heaters where extracted steam from the LP turbine is in two-phase state.
6) Calculate heat balance of HP turbine, LP turbine, feed water pump turbine, etc. Calculate ELEP enthalpy by condenser heat input divided by exhaust flow of LP turbine
7) Assume new ELEP as calculated in 6) and repeat step 4)-6) until ELEP deviation is less than 0.1 Btu/lbm.

After these calculations, Corrective heat balances of group #1 and group #2 are calculated for comparative analysis of performance. In group #1 correction, equipment conditions except turbine are assumed as in initial design status of power plant and heat balance is calculated again using these conditions. In group #2 correction, cycle efficiency and heat rate is corrected for variables that have direct effects on turbine cycle. Major correction variables are such as TTD (Terminal Temperature Difference) and DCA (Drain Cooler Approach) of feed water heater, pressure drop, main feed water pump turbine status, condenser sub-cooling, condenser make-up, power factor, H2 pressure of turbine, steam generator blow down, condenser pressure, stop valve moisture & pressure and thermal output, etc. Correction curves are fitted using vendor supplied data [8] and used in our NOPAS system through user customization process.

Performances of each component in turbine cycle are calculated. Internal efficiency of turbine is calculated for high-pressure turbine and re-heat turbine from inlet and outlet conditions of turbine. The efficiency is calculated from status of extracted stage, outlet steam pressure and expansion line. Moisture of extracted steam is calculated using iterative calculation started from dry stage efficiency condition. Performance of generator is defined as ratio of generator output to turbine output. Loss in turbine and generator is calculated from mechanical loss and generator loss determined from power factor and H2 pressure. Input for performance calculation of condenser is turbine cycle status, cooling water temperature, number of tube plugging, etc. Performance indexes for condenser are thermal effectiveness, LMTD (Log mean Temperature Difference), cleanliness factor and TTD, etc. Performance indexes for feed water heater are TTD and DCA. According to state of drain, feed water heater are classified as 3-Zone, 2-Zone, 1-Zone FWH and the performance of each FWH is calculated using separate procedures. Performance of FWH is calculated from heat balance data of turbine cycle, tube plugging number and drain level, etc. Moisture separating effectiveness of MSR is also calculated using heat balance data of MSR. Thermal effectiveness and TTD of re-heater is calculated form heat balance data.

3. Modifications in Operating Performance Calculation

Suppliers of nuclear power plant equipment in Korea are so various that unified model for performance calculation of turbine cycle could not be easily implemented. Therefore we need some modifications on the general procedures of performance calculation based on ASME PTC. We developed flow network model including all of turbine cycle in domestic nuclear power plants. To develop unified and consistent procedures of performance calculation, we should adapt the procedures to compensate for various characteristics of the domestic power plants. [10] The adaptations that we proposed were focused in following categories,

- Method to estimate ELEP and enthalpy of extracted steam
- Consistency between design performance procedure and operating performance procedure

New procedures to estimate ELEP are required to unify the performance evaluation of turbine cycle. We developed the estimation of new ELEP using linear polynomial regression on H-P (Enthalpy-Pressure) diagram rather than curvature approximation on H-S (Enthalpy-Entropy) diagram. Iteration of turbine cycle calculation can be reduced about 20 % using this approach. In order to use these routines of operating performance calculation with cause-effect analysis and improvement analysis, consistency between calculation procedures of operating performance and design performance should be established. We developed performance calculation modules to ensure this consistency. Sensitivity analysis using the consistent procedure must be developed to quantify the effect on system degradations.

Robustness in performance calculation must be increased to produce a calculation result of performance in case of some errors of measurement values. We modified performance calculation procedures to decrease the possibilities of run-time calculation error. Although basic principles in ASME PTC can' t be modified, approximation rules can be modified to reduce calculation errors. Especially, state properties of extracted steam are very sensitive to mass flow quantities because enthalpy is calculated using heat balance equation including mass quantity that has relatively very larger value than enthalpy. These incorrectly estimated value has a tendency to cause run-time error in the calculation of turbine expansion line during iterative calculation of overall heat balance of turbine cycle. Calculation robustness is increased using assumption of linear enthalpy distribution in HP and LP feed water line rather than linear pressure distribution assumption.

Acceptance measurement data of feed water temperature (T), pressure (P) and enthalpy (H) of feed water heater line of Kori 3 unit in 100% load and VWO (Valve Wide Open) condition is represented in Table 1. State id represents state point. For example, H-FWH#2_outlet means feed water outlet point of #2 high pressure feed water heater. Ratio value is obtained from start point of high and low feed water heater line,

Table 1. Feed Water Temperature, Pressure and Enthalpy of Feed Water Heater Line of Kori 3 Unit

State Id	Load	T	H	P	T ratio	H ratio	P ratio
H-FWH#2_outlet	VWO	229.2	987.3	65.09	1.000	1.000	1.000
H-FWH#1_outlet	VWO	186.6	795.6	78.20	0.380	0.372	0.129
H-FWH#1_inlet	VWO	160.5	682	80.14	0.000	0.000	0.000
H-FWH#2_outlet	100	226.6	975.5	75.26	1.000	1.000	1.000
H-FWH#1_outlet	100	184.4	785.7	73.78	0.379	0.371	1.311
H-FWH#1_inlet	100	158.6	673.8	80.02	0.000	0.000	0.000
L-FWH#4_outlet	100	143.3	604.6	24.57	1.000	1.000	1.000
L-FWH#3_outlet	100	106.2	447.1	26.48	0.656	0.658	0.642
L-FWH#2_outlet	100	71.0	299.3	26.58	0.333	0.338	0.309
L-FWH#1_outlet	100	55.5	234.5	26.58	0.192	0.194	0.179
L-FWH#1_inlet	100	34.5	146.6	23.78	0.000	0.000	0.000

respectively. Linear distribution of pressure along feed water line was normally assumed in performance calculation previously, but the distribution of pressure along low pressure feed water heater line has not linear distribution as shown in Table 1 and the linear assumption should be modified for more accurate calculation.

Four measurement data of feed water enthalpy of low pressure feed water heater line of Kori 3 unit in 100% load are represented in Fig. 4. Fig. 4 reveals that there is fixed ratio between each point of feed water enthalpy in FWH line. We construct estimation formula for enthalpy of FWH inlet steam using these ratios. This approach reduces the sensitivity of heat balance calculation to incorrect measurement input of inlet and outlet status of feed water heater.

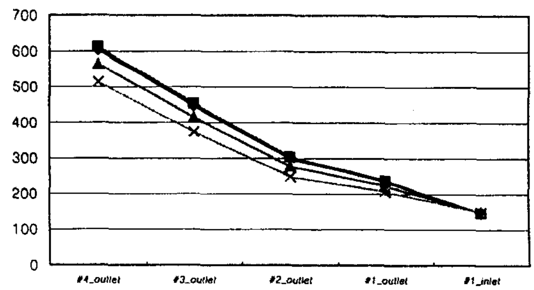

Fig. 4. Enthalpy of Steam Inlet of Low Pressure Feed Water Heater

4. Input Validation and Verification

As operation of power plant continues, more calibrations and validations are required for measurement sensors. There are many causes for invalid collection of performance measurements including malfunction of signal processing. As a physical example, fouling of venturi surface of flow rate sensor is increased due to chemical reactions and deposits.

We assumed that initial acceptance data and design data of domestic power plants could provide correlation information between measurement data. These data can be used as sample sets of the estimation relation for the correct measurement data. The estimation relation can be modeled using associative memory or multi-layer perceptron neural network [7]. The output layer is the estimating measurement variable and the input layer is constructed using measurement variables that

Table 2. Correlation Coefficients Related to Important Measurement Variable

Measurement	Most correlated variable	Correlation coefficient	Usefulness
Generator Output	S/G Inlet Feed water Flow (WWsg_i)	0.991	
(KWgn_o)LP3	FWH Outlet Drain Flow (WDl3_o)	0.957	
	MSR Separator Drain Flow (WDrs_o)	0.939	
Moisture of Outlet	LP #4 Ext. Steam Pressure (PElt_4)	0.962	
Steam of Steam	LP #3 Ext. steam Pressure to FWH (PElt_3)	0.906	
Generator (MSsg_o)	Generator Power Factor (PFgn)	0.877	
Condenser	Condenser Outlet Condensate Temperature (TWmc_o)	0.990	
PressureCOP	Outlet Condensate Temperature (TWcp_o)	0.974	
(PSmc_in)	LP1 FWH Inlet Condensate Temperature (TWl1_i)	0.893	
LP1 FWH Outlet	HP1 FWH Outlet Drain Flow (WDh1_o)	0.522	N/A
Drain Flow	HP1 FWH Inlet Feed water Pressure (PWh1_i)	0.466	N/A
(WDl1_o)	LP3 FWH Inlet Ext. Steam Press (PEl3_i)	0.457	N/A
S/G Inlet Feed water	HP1 FWH Inlet Feed water Temperature (TWh1_i)	0.564	N/A
Pressure	HP1 FWH Inlet Feed water Pressure (PWh1_i)	0.553	N/A
(PWsg_i)	MFP Inlet Feed water Temperature (TWmp_i)	0.551	N/A
LP3 FWH Outlet	LP3 FWH Inlet Condensate Temperature (TWl3_i)	1.000	
Drain Temperature	LP2 FWH Inlet Ext. Steam Press (PEl2_i)	0.998	
(TDl3_o)LP1	FWH Inlet Ext. Steam Press (PEl1_i)	0.985	
MSR 2nd R/H	Drain MSR 2nd R/H Outlet steam Temperature (TSr2_o)	0.981	
Temperature	2nd R/H Inlet Heating steam Pres (PEr2_i)	0.970	
(TDr2_o)	S/G Internal Steam Pressure (PSsg)	0.962	
MSR Separator	HP TBN Exhaust steam Pressure (PSht_o)	0.983	
Drain Temperature	MSR Separator Inlet steam Pressure (PSrs_i)	0.976	
(TDrs_o)	MSR 2nd R/H Outlet steam Pressure (PSr2_o)	0.969	

are mostly correlated. Learning data is supplied to determine neural network parameters using design heat balance, acceptance heat balance and heat balance that was confirmed to be valid. But, the relation can be practically modeled using regression model [11] based on sample data of plant design data without loss of precision, plant acceptance data and verified performance measurements. New algorithms for input verification and validation that we suggest can be summarized as,

- Select 3 most correlated input measurements for the measurement item from 80~120 measurement input data. Data set is obtained using design heat balance, acceptance heat balance and heat balance that was confirmed to be valid. Data set of Kori, Uljin, Wolsung and Youngkwang power plant are used in.
- Estimation model is comprised of above correlation data set using regression model

Most correlated variables are selected using Pearson product-moment correlation coefficient [11] as Eqn. (1).s

Table 3. Estimation Result for Validation of Input Measurement

Measured PElt_1	Estimated PElt_1	Estimation Error (%)	PWmp_i	TWsg_i	PEht_1
62.59	62.47	0.19	290.02	433.82	396.77
64.35	64.40	-0.08	340.01	429.74	378.47
65.02	65.80	-1.20	380.37	439.46	420.19
70.33	70.29	0.06	494.95	426.82	371.11
49.07	49.06	0.02	46.56	367.47	187.18
67.16	66.58	0.86	374.63	440.01	422.83
64.10	63.99	0.17	488.82	444.92	429.80
64.48	64.63	-0.23	489.85	446.61	431.22

$$r_{ij} = \frac{s_{ij}^2}{\sqrt{s_{ii}s_{jj}}} \quad \text{where} \quad s_{ij}^2 = \frac{\Sigma(y_i - \overline{y_i})(y_j - \overline{y_j})}{N-1} \qquad (1)$$

Table 2 shows correlation coefficients related to some important measurement variable. The selected variables for the estimation of generator output are S/G inlet feed water flow rate, LP3 FWH outlet drain flow and MSR separator drain flow. For condenser pressure that is sensitive to turbine cycle heat rate, condenser outlet condensate temperature, COP (Condenser Pump) outlet condensate temperature and LP1 FWH inlet condensate temperature are selected.

But maximum correlation coefficient of LP1 FWH outlet drain flow rate (WDl1_o) and S/G inlet feed water pressure (PWsg_i) in Table 2 are not greater than 0.6, so the estimation model that we proposed could not be applied to these variable. These items are marked as "N/A" in usefulness column of Table 2. Among 65 measurement items, 7 data item has maximum correlation value below 0.82. Therefore, the estimation algorithm we proposed could not be used for validation of these measurements. New algorithms for verification and validation must be developed in different approaches. Drain flow measurements have relatively low correlation values than

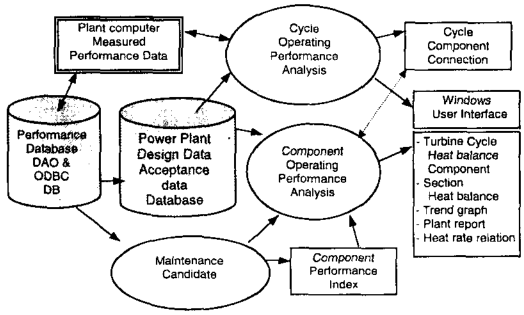

Fig. 5. Database Module and System Flow of Windows-NOPAS

pressure and temperature variables.

As an another example, correlated variables for #1 extracted steam pressure of low pressure turbine (PElt_1) are MFP (Main Feed water Pump) inlet feed water pressure (PWmp_i), S/G inlet feed water temperature (TWsg_i), HP #1 Ext. STM pressure to FWH (PEht_1). Table 3 represents estimation results using these variables and heat balance data. Maximum value of estimation error was 1.2%, so estimation model can be justified as a practically useful estimation model.

5. NOPAS System Interface

NOPAS system flow is constructed as in Fig. 5. Modules in performance database are

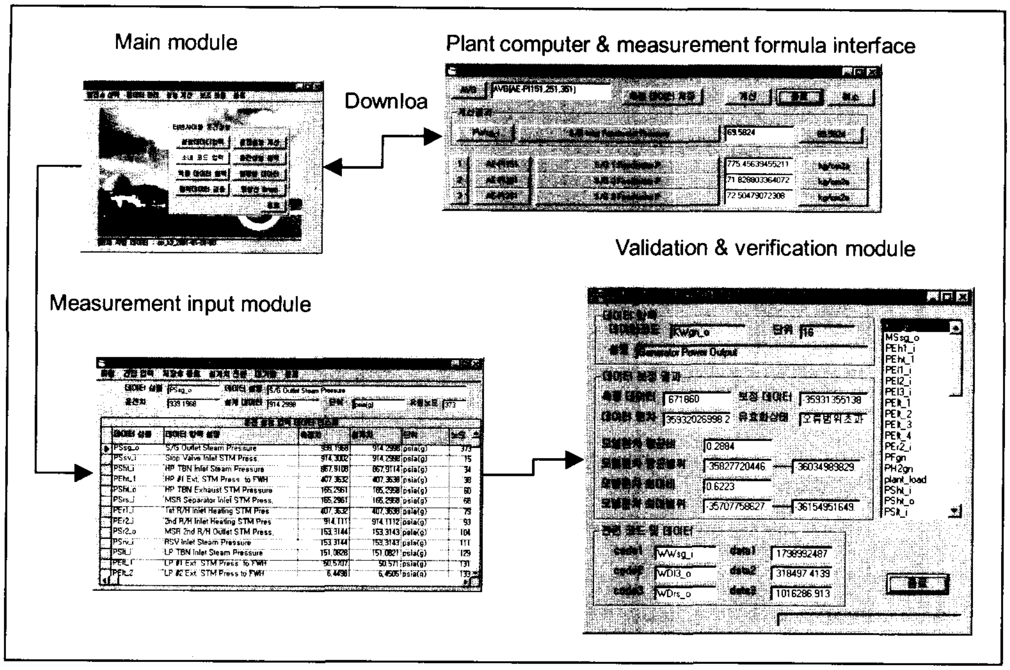

Fig. 6. NOPAS Input Module with Validation & Verification

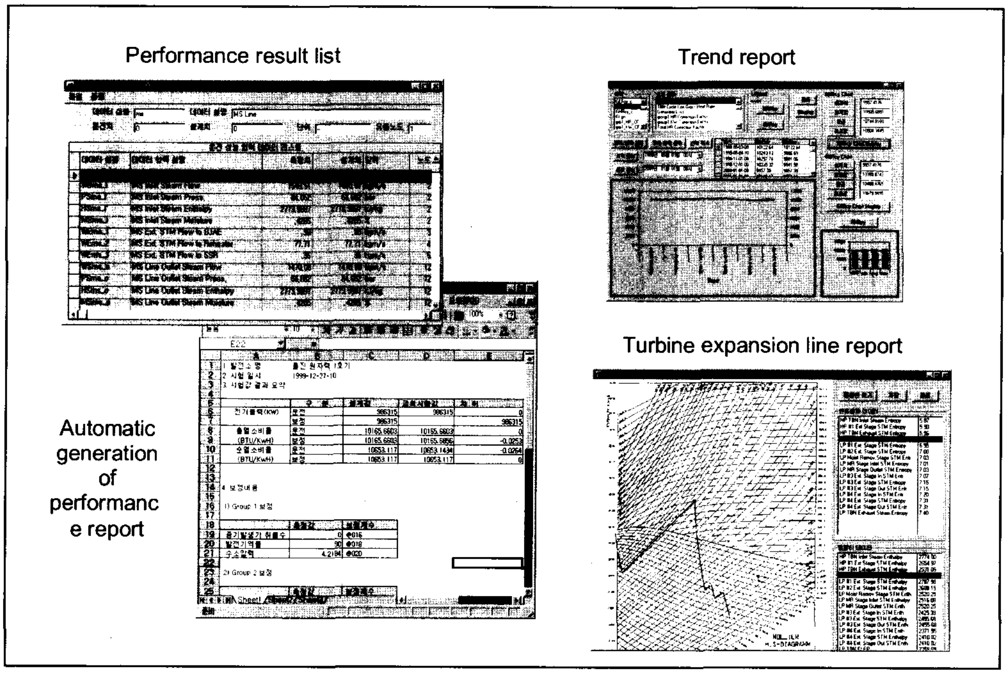

Fig. 7. NOPAS Output Module with List, Trend, Expansion Line and Report

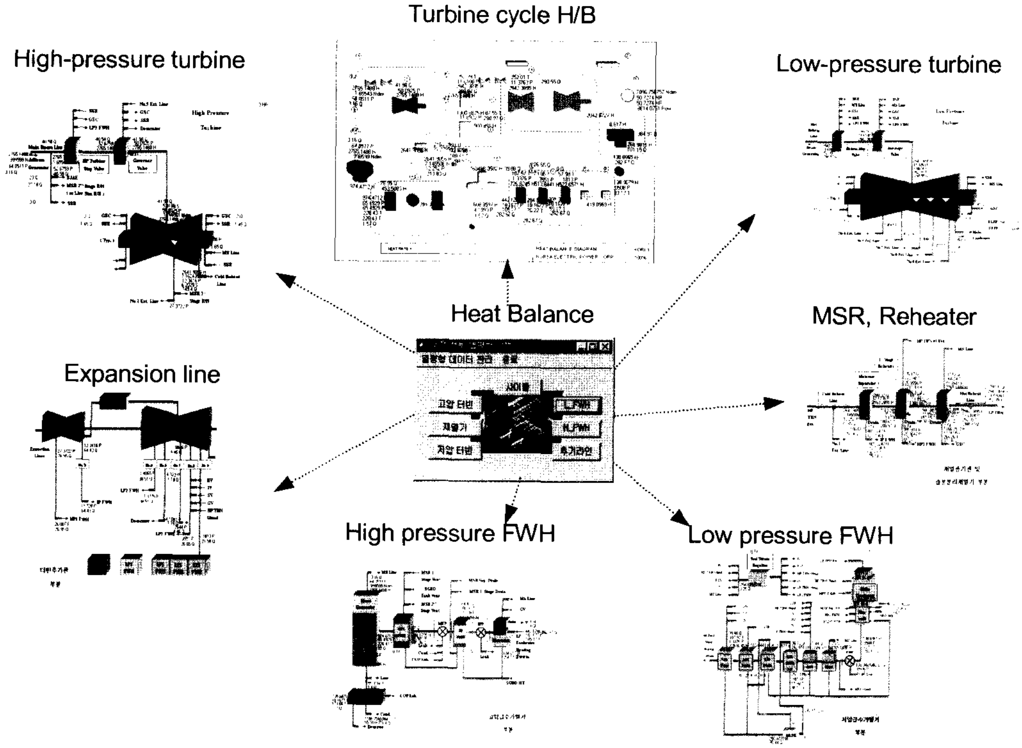

Fig. 8. NOPAS Heat Balance Output Module

grouped as validation module, performance data module, plant design data module, measurement data module and output module. Database is constructed using Microsoft Jet Database and DAO (direct access object) interface [12]. All domestic plant data has same codes for performance data item. Maximum flow network incorporating all structure of turbine cycle in domestic power plant is established and stored in node table structure. Module for thermal output is constructed according to each plant' s data structure and calculation procedures.

Fig. 6 represents user interface for measurement data input. It provides function of input range checking, plant computer data linking and validation and verification of input and default design data for unmeasured item. Using this module, user can input performance measurements conveniently. Validation module reveals correlated input items and validation results. User can customize input unit set among SI, metric and English unit set and can choose absolute pressure or atmospheric pressure input. Also, user can customize individual unit item and symbol for each performance data item.

Fig.7 represents major analysis outputs after performance calculation. List result provides calculation result of total turbine cycle and component performance. These results of component performance include high pressure turbine, low pressure turbine, steam generator, moisture separator, re-heater, condenser, low pressure feed water heater, high pressure feed water heater and pumps. It provides trend data with graphic summary information. Turbine expansion line report reveals change of turbine state from it' s acceptance stage. Also, turbine expansion line represents core information about moisture separation and turbine efficiency. User can customize spreadsheet-based report for performance analysis and all result of performance analysis is automatically summarized in spreadsheet report file.

Fig.8 represents heat balance result reports. Summary heat balance of turbine cycle is provided and sub-section of heat balance is displayed. These sub-sections includes high pressure turbine section, low pressure turbine section, MSR-reheater section, extraction line section, condenser and low pressure feed water heater section and high pressure feed water heater and S/G section. User can customize heat balance graphic image report by selecting display data item and locations. As auxiliary modules, thermal output, steam table and curve fitting modules for correction approximation are provided in NOPAS system.

6.Conclusions

We developed a performance analysis system that can be used in most of the domestic nuclear power plants. The system generates consistent performance analysis based on validation and verification of performance measurement data. We used algorithm in which estimation relation for validated measurement can be obtained using correlation model between measurements. The general procedures of performance codes are modified and successfully applied to the domestic nuclear power plants. Besides performance calculation results of turbine cycle and components, NOPAS system provides graphic heat balance, turbine expansion line and customized report. We found practical usefulness of this system to provide reliable performance analysis of domestic nuclear power plant.

Acknowledgements

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