Impact of the Thermal Energy Storage System on APR1400 Turbine

Anna M. Kluba*[a], Robert M. Field[b], Byoung Seung Kim [a], Youngsuk Bang [a]
[a] *Department of Advanced Technology Development, FNC Technology Co., Ltd.*
32Fl., 13 Heungdeok 1-ro, Giheung-gu, Tongin-si, Gyeonggi-do, 16954, Korea
[b]*Department of Nuclear Power Plant Engineering, KEPCO Internatonal Nuclear Graduate School,*
658-91 Haemaji-ro, Seosaeng-myeon, Ulju-gun, Ulsan, 45 014, Korea
**Corresponding author: annkluba@gmail.com*

1. Introduction

The nuclear industry supports global efforts to reduce carbon dioxide (CO_2) emission. Nuclear Power Plants (NPPs) as a clean and reliable power sources are key contributors to achieve carbon neutrality in near term. The alternative technologies characterized by very low carbon footprint are hydropower plants and renewable energy generation such as wind farms or photovoltaic power stations. The endeavors undertaken to transform energy systems towards achieving carbon neutrality (i.e. Nuclear Renewable Hybrid Energy System) focus on measures needed to integrate all the aforementioned power sources into reliable system. Particularly, the challenge related to intermittent nature of renewable energy sources (i.e. wind and solar) resulting in severe cyclic duty of dispatchable energy sources shall be addressed.

NPPs are predominantly operated as base load units. Technical issues, aging of large equipment, and challenged economic viability are only few examples of the consequences resulting from load following NPP operation [1]. However, there are solutions that can provide enhancement of NPP output flexibility. For instance Thermal Energy Storage (TES). The integration of NPP and TES enables plant to maintain full reactor power while generator varies output following demand of an energy system. The implementation of TES technology requires various engineering analysis to assure safe, efficient, and reliable plant operation.

Here, the investigation focuses on the impact assessment of TES installation on the Turbine Generator (T/G). The presented evaluation continues work previously published. The preceding investigation focuses on the Nuclear Heat Storage and Recovery (NHS&R) System design, optimization, and operational impact. The NHS&R System is designed to be integrated with Korean Advanced Power Reactor with net generator output 1400 MW_e (APR1400) [2,3]

2. Background

2.1. APR1400 T/G

The APR1400 T/G is an 1800 rpm tandem-compound four flow reheat unit with 52-inch Last Stage Blade (LSB) provided by Doosan Heavy Industries. The turbine consists of the four (4) sections; a double flow High Pressure (HP) section and three (3) double flow Low Pressure (LP) sections. Exhaust steam from the High Pressure Turbine (HPT) passes through two (2) parallel two-stage Moisture Separator Reheaters (MSR) before entering the Low Pressure Turbines (LPTs).

The HPT is designed to operate with partial arc steam admission. The Extraction Steam (ES) is supplied from various HPT stages to 1st stage MSR and to HP Feedwater Heaters (FWH) No. 5, 6, and 7.

The steam extracted from the LPTs is supplied to Deareator (DA) and LP FWHs No. 1, 2, and 3. The LPT has updated moisture removal features.

The main generator is a direct-driven, three-phase, 60 Hz, 24kV, four-pole synchronous generator. The generator is rated at 1,690 MVA at a 0.9 power factor. The generator has water-cooled armature windings and hydrogen-cooled rotor. [4] The simplified diagram of APR1400 secondary cycle is illustrated in Fig. 1.

The APR1400 T/G is designed to prevent damage under failure mode condition. The failure modes incorporate the following: (i) Stress Corrosion Cracking (SCC), (ii) Turbine Water Induction (TWI), (iii) T/G overspeed, and (iv) torsional vibration.

Furthermore, in the original design of APR1400 T/G set there is included margin to account for uncertainties in the actual operating power level and actual steam flows. The APR1400 turbine is designed for Valves Wide Open (VWO) condition with a throttle flow margin around 5% greater than the Maximum Guaranteed Rate (MGR).

2.2. The NHS&R System – Design and Operation

The NHS&R System is a conceptual design of sensible heat storage interfaced with secondary system of APR1400 via shell-and-tube heat exchangers. Synthetic oil (e.g. Therminol 66) is selected as heat transfer and heat transport medium of the tertiary cycle The heat is stored in crushed rock (e.g. Hornfels) enclosed in insulated storage tanks.

Under the NHS&R heat storage operation 20% of Nuclear Steam Supply System (NSSS) thermal power (~800 MW_t) is extracted the heat from Main Steam (MS) to the tertiary cycle. The heat is transferred in Oil heaters located in Heat Storage Building (HSB). The condensed steam is routed back to the secondary cycle and flashed into the DA.

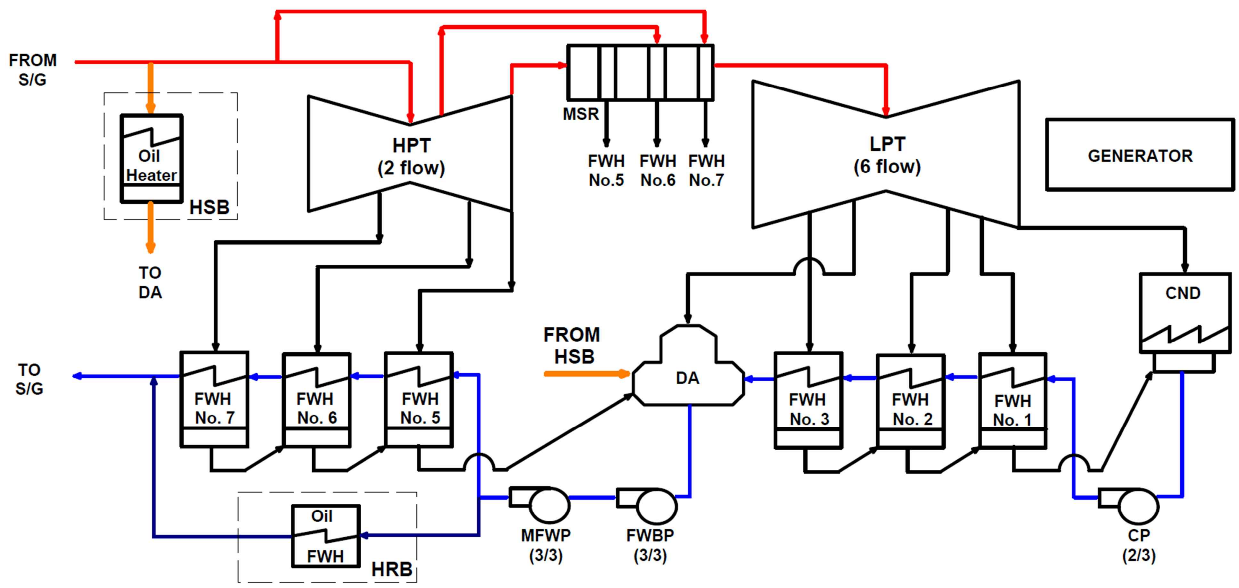

Fig. 1. Simplified diagram of APR1400 Secondary System coupled with the NHS&R.

Under heat recovery operation ~11% of NSSS (~450 MW_t) is transferred the turbine cycle by preheating fraction of Feedwater (FW) (~45% of the main FW stream) in supplementary FWHs located in Heat Recovery Building (HRB). [2]

The previous investigation identified key impact of the NHS&R integration on APR1400 plant operation. [2]. Particularly, Final Feedwater Temperature (FFT) variation indicated as primary concern. The storage operation results in FFT reduction, while as a consequence of recovery operation FFT increases. This temperature changes are compensated by FW flow regulation to keep NSSS power at constant level. The evaluation proposed APR1400 control system adjustment to address FFT fluctuation. [3]

3. Methods

The impact assessment of the NHS&R System on the APR1400 T/G performance were carried out by comparison of the key performance data of the T/G under VWO, MGR, Heat Storage and Heat Recovery operation modes. The data were acquired as a results of computational simulations of validated APR1400 turbine cycle model .

3.1. Thermodynamic Model Simulation

The APR1400 Rankine cycle alone and coupled with the NHS&R System were simulated using the Performance Evaluation of Power System Efficiencies (PEPSE®) software. PEPSE® evaluates steady state thermodynamic performance of each of the simulated components and the entire system by application of fundamental physical laws (i.e. conservation of mass and energy, pressure change, heat transfer effects).

First, the model of APR1400 secondary cycle was developed to reflect a base load plant operation. The model calibration was performed in reference to data provided in the APR1400 Design Control Documents (DCD) available to the general public [4]. The customized modeling of Total Exhaust Loss (TEL) was provided. The TEL curve specific to GE 52" Last Stage Blade (LSB) (Fig. 1) was incorporated into the calculation together with correction term corresponding to moisture content in a steam and fictitious stage efficiency (Eq. 1) present in the literature. The detailed method is present elsewhere [5].

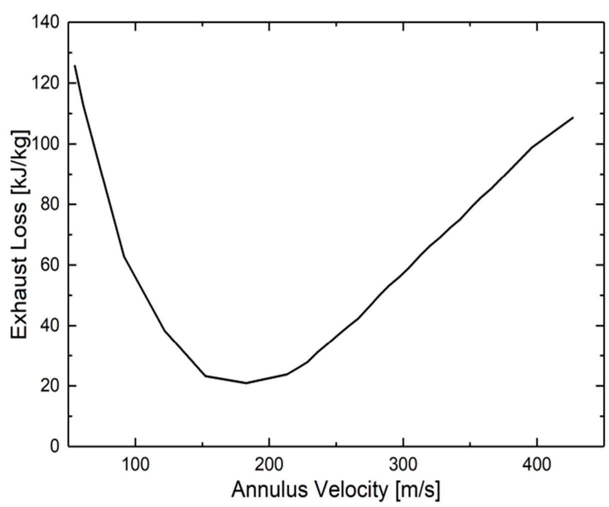

Fig. 2. Total Exhaust Loss curve for GE 52" LSB.

$$H_{UEEP} = H_{ELEP} + TEL(1-0.01Y)0.87(1-0.0065Y) \quad (1)$$

where H_{UEEP} – enthalpy of Used Energy End Point (UEEP) (BTU/lb_m), H_{ELEP} – enthalpy of Expansion Line End Point (BTU/lb_m), *TEL* – Total Exhaust Loss (BTU/lb_m), Y – percent weighted average moisture at the ELEP (%). The validated model was modified to reflect the interface arrangement with the NHS&R System under storage and recovery operation.

3.2. Effective Throttle Flow Ratio

During recovery operation MS flow to the turbine is expected to increase as compared to MGR conditions. Therefore the flow passing capability for APR1400 HPT under recovery operation needs to be verified. The heat balance data are used to estimate the flow margin by calculating Effective Throttle Flow Ratio (ETFR) according to following formula (Eq. 2) [6].

$$ETFR = \left(\dot{m}_{NHS\&R} \, / \sqrt{(\frac{p}{v})_{NHS\&R}} \right) \Big/ \left(\dot{m}_{VWO} \, / \sqrt{(\frac{p}{v})_{VWO}} \right) \quad (2)$$

where, *EFTR* – effective throttle flow ratio (-), $\dot{m}_i$ – Control Valve (CV) steam inlet mass flow rate (lbm/hr), p_i – CV steam inlet pressure (psia), v_i – CV steam inlet specific volume (lb_m/ft^3). The throttle flow margin is a difference between one (1) and EFTR. The acceptable margin should be greater than 1% to provide reliable operation of the plant, primarily to ensure adequate reactor vessel pressure control.

4. Results and Analysis

4.1. Impact on throttle flow margin

The EFTR evaluation data and results are presented in Table 1. Export of MS to HSB during heat storage operation reduces the steam flow rate supplied to the HPT admission, hence the throttle flow margin is significantly higher. Note that APR1400 HPT is designed to operate with partial arc admission what reduces energy losses due to throttling during low load operation.

Table 1: Throttle Flow Margin.

Operation Mode	VWO	MGR	Storage	Recovery
$\dot{m}$, 10^3 lb_m/hr	18,023	17,164	13,652	17,635
p, psia	962.0	962.0	965.9	941.3
v, ft^3/lb_m	0.464	0.464	0.462	0.475
ETFR, -	1.00	0.95	0.75	1.00
Margin, %	0%	5%	25%	0%

The CV steam inlet mass flow rate under recovery operation is bounded by VWO condition however due to lower MS pressure the margin does not satisfy the criteria (Section 3.2.). However, minor steam path modification could increase the margin to acceptable level and these would not adversely impact the turbine bearings and pedestals.

4.2. Impact on steam flow path conditions

The inherent design margin (see Section 2.1.) of APR1400 T/G for VWO condition sets the acceptance criteria for operation beyond MGR condition. Therefore any condition bounded by VWO conditions is acceptable.

The pressures and mass flow rates associated with individual Stage Group (S.G.) of APR1400 turbine under storage and recovery operation were compared to VWO conditions and illustrated in Fig.3. The S.G. parameters with a positive margin are bounded by inherent design margin. Conversely, the parameters with negative margin exceed VWO conditions.

The conditions beyond VWO operation are indicated for recovery operation from 2nd stage group of the HPT to the LPT exhaust. Over the recovery operation the FW is preheated in partial bypass thus the ES supplied to HP FWH is reduced resulting in higher interstage parameters.

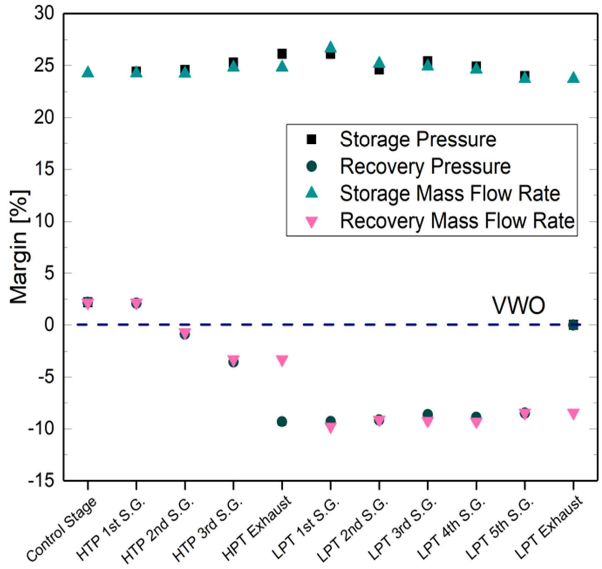

Fig. 3. Margins of pressures (p) and mass flow rates ($\dot{m}$) overt the APR1400 turbine steam flow path.

The industry experience of power update programs in e.g. the USA, Taiwan, Spain, and Mexico indicated that steam flow path and many of the T/G structural components demonstrated to have margin exceeding VWO condition without significant modification. Therefore, the parameters present during recovery operation may be accepted after vendor revision. Nevertheless the vendor detailed revision is required prior implementation.

The steam quality along the steam flow path under NHS&R operation compared with MGR operation is shown in Fig.4. The offset of the quality values is close to the base load value (no greater than 2%). Thus the risk of erosion of turbine blades due to excessive moisture content is considered to be minimal.

The power generated by each of the stage groups is presented in Fig. 5. The extra power output during heat recovery operation is generated by the LPT. There may be required some LPT steam flow path modifications to lower the HPT back pressure what would result in increased HPT wheel power and reduce the load on the LPT S.G.

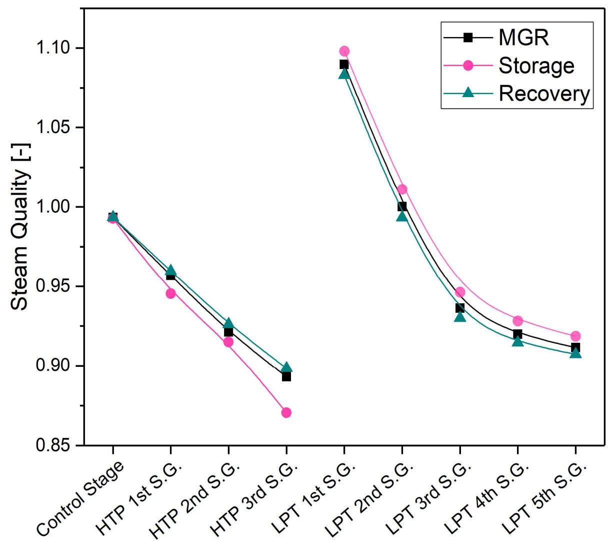

Fig. 4. Steam quality – APR1400 turbine steam flow path.

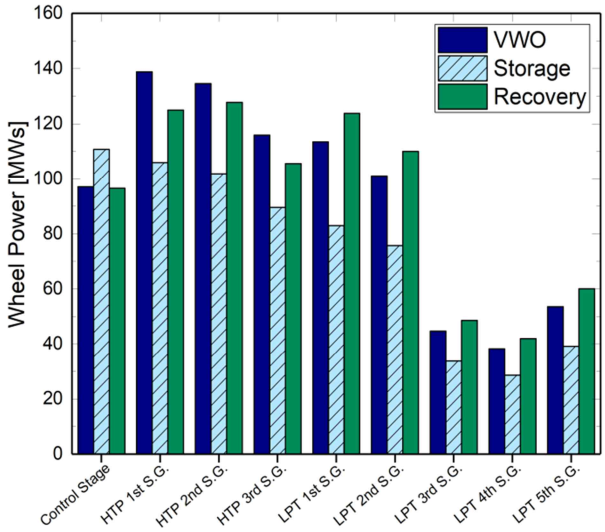

Fig. 5. Wheel power for each of the Stage Groups (S.G.s) of the APR1400 turbine under different operating modes .
Note that the LPT S.G.s wheel power is for one (1) section out of three (3).

4.3. Failure modes

The APR1400 T/G failure modes addressed by appropriate design and operation are listed in section 2.2.

Industry standards and practices eliminated risk of SSC and TWI occurrence entirely, hence these events are excluded from the analysis.

Turbine overspeed occurrence is expected when balance between a torque generated by the turbine is not balanced by an electrical load flow is lost. As a result of this event shaftline accelerates immediately, therefore with no action taken could lead to T/G damage. Turbine overspeed protection system isolates the turbine when abnormal conditions are detected.

The addition in thermal energy during heat recovery operation increases energy stored in the turbine system thus the turbine overspeed trip device settings shall be reviewed.

T/G torsional vibration related to mass and stiffness along the shaftline which remains unchanged under the NHS&R operation. The integration is expected to have slight or no impact on the harmonic frequencies due to changes in transmitted torque and power. Therefore, the NHS&R operation does not increase the risk of T/G shaftline failure due to torsional vibration.

4.4. Impact on APR1400 Main Generator

The considerations for main generator can be narrowed down to analysis of the recovery cycle performance as the generated output exceed base load operation. The acceptance criteria for generator is to operate within limits of the capability curve.

Heat recovery results in increased Main Generator power output to 1,586.4 MW_e it is approximately 9% over the MGR condition. Power generation at this level can be supported by APR1400 main generator rating. However, this requires operation at power factor 0.95 lagging what reduces grid voltage support. To maintain stable grid recovery operation shall be discussed with grid operator.

5. Conclusions

The impact assessment of the NHS&R System on the APR1400 T/G was presented. The evaluation indicated no adverse effect of the storage operation on the T/G set. There are no identified major issues which would foreclose implementation of the system. However, under recovery operation some parameters exceeded VWO condition therefore comprehensive vendor review is required prior implementation of the APR1400 NHS&R System.

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