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Determination of Preliminary Plant Operation Logic for KALIMER

Yeon-Sik Kim, Yoon-Sub Sim, and Eui-Kwang Kim

Korea Atomic Energy Research Institute
150 Dukjin-dong, Yuseong-gu, Taejon, Korea, 305-353

Abstract

In the KALIMER design, once-through helical coil steam generators are used to generate superheat steam. The once-through steam generator has its unique operational characteristics and a preliminary scheme for plant operation temperature. The operation temperature scheme determines typical thermal behaviors of the main systems in the plant and is the starting point in setting up the plant operation logic. Control features in plant operation between PWR and LMR are discussed including several technical aspects that need to be considered in developing the plant operation logic. Using HSGSA-RE code, calculational results on the operation logic are obtained. Based on the results, a preliminary operation logic for KALIMER is proposed.

1. Introduction

The KALIMER steam generator is a vertically oriented helical coil type heat exchanger with sodium-to-water counter-cross flow. For the tube side, water flows and is converted to steam. For higher plant efficiency, a once through superheated steam cycle has been adopted in the KALIMER steam generating system [1]. A computer code, named HSGSA (Helical coil Steam Generator Sizing Analyzer), was developed for the thermal sizing analysis of the KALIMER steam generator in the previous work [2].

A once-through superheated steam generator is apt to have unstable operational characteristics at a low power range. To overcome this instability, the steam generator is usually operated in a saturated recirculation mode for low power or low flow conditions. To determine a plant operation logic, a tool to simulate the saturated recirculation mode is needed and an extended version of HSGSA, named HSGSA-RE (Helical coil Steam Generator Sizing Analyzer-including REcirculation mode), is developed. The code uses almost the same algorithm that HSGSA uses. Using the HSGSA-RE computer code, a preliminary plant operation logic of KALIMER is developed. In developing the plant operation logic, several technical aspects should be also considered and are discussed in the following sections.

2. Preliminary Plant Operation Logic

2.1 Plant Operational Features in PWR vs LMR

In a nuclear power plant, the magnitude of plant thermal power is equal to the product of the steam flowrate and enthalpy difference. For subcooled coolant flow, specific heat can be assumed constant and the enthalpy difference becomes proportional to the temperature difference. In controlling the plant thermal power requirement, there are many possible ways, such as manipulating the flowrate and/or temperature difference. Most of the current pressurized light water reactors (PWRs) adopt the scheme of constant flowrate and sliding coolant average temperature (T_{avg}) for the plant power control.

As in the PWRs, liquid metal reactors (LMRs) also adopt a sliding T_{avg} control scheme in the primary system as the basic plant operation logic. The sliding T_{avg} control is the compromised scheme between the constant T_{avg} control scheme and the constant P_{steam} control scheme. The compromised scheme results in medium variation in the primary average temperature and steam pressure and the variation also introduces medium changes in the variation of the primary coolant volume and inventory, reactivity, and the steam pressure. The main difference in the design features between the PWR and current LMR is in the system configuration: primary and steam systems for the PWR vs primary, intermediate and steam systems for the LMR. In the LMR design, the intermediate system is introduced as the barrier to radioactive coolant and to lessen the possible sodium-water reaction consequence for protection of the primary loop.

Fig. 1 is shown as an example of the sliding T_{avg} control logic in the PRISM MOD-A, which uses a saturated steam cycle [3]. As shown in Fig. 1, the steam temperature (or pressure) is deeply dependent upon the intermediate cold temperature in the saturated steam cycle plant. Also the steam temperature is equal to and/or lower than the intermediate cold temperature. This tendency can also be found in the PWR plants. In UCN 3,4, the first Korean Standard Nuclear Power Plants, the steam temperature is equal to the primary cold leg temperature at the zero power level [4]. Above the zero power level, the steam temperature is always below the primary cold leg temperature and the temperature differences between them become larger in proportion to the power level as shown in Fig. 2. This is due to using a recirculating type evaporator in generating steam in the saturated cycle.

On the contrary, the steam temperature in the superheated steam cycle is mainly dependent on the intermediate hot leg temperature as shown in Fig. 3 of CRBR that uses sliding T_{avg} control logic [5]. The CRBR plant adopts superheated steam cycles and whose steam generating system consists of an evaporator for saturated steam and a reheater for superheated steam. The saturated steam from the evaporator is transferred to the reheater and converted to superheated steam. KALIMER also adopts the sliding T_{avg} control logic for the primary and intermediate systems, and a superheated cycle for the steam system for better plant efficiency. But the KALIMER steam generating system uses a once-through steam generator as an integral evaporator and reheater.

The dominant differences in the power operation controls between the PWR and the LMR are compared in Table 1.

2.2 Plant Operation Modes

The KALIMER adopts a superheated steam cycle with a once-through helical coil steam generator, which conceptually contains an integral evaporator and reheater. A steam generator of this type is generally weak to flow instability at a lower power range. Generally, possible or recommendable remedies to enhance flow stability are increases of inlet restriction, operating pressure, and flow rate [6]. Among these, the increase of inlet restriction is practically adopted in the plant design since the others are not as flexible as the inlet restriction increase. If flow stability is to be maintained for all the power ranges in KALIMER, a very large pressure drop is required and the required feedwater pumping power becomes huge. This is the reason why some optimization is needed to determine practical restrictions. For example, the PRISM MOD-B steam generator has an orificing restriction equivalent to 0.7 MPa pressure drop and recirculation mode is operated up to 25% power [7,8].

The KALIMER is operated as the saturated recirculation mode for the lower power level. In the KALIMER steam generator, a flow restricting orifice which is equivalent to 1.0 MPa pressure drop is equipped at each tube inlet to prevent flow instability above 25% power level, and a saturated steam cycle with recirculation is used from the startup to 25% power and then the steam cycle mode is changed to a once-through superheated steam cycle for 25% to 100% power. Fig. 4 shows the schematic diagram of the operation modes in KALIMER. For the recirculation operation of an auxiliary tank, which separates steam from the two-phase mixture coming from the steam generator, is equipped adjacent to the steam generator in KALIMER. As aforementioned, to determine the operation logic for the lower power range, HSGSA-RE is developed and it has the capability of estimation of the plant condition for saturated recirculation operation.

2.3 Assumptions and Restraints

In the determination of the plant control logic, the initial assumptions are quite important. The general logic for primary and intermediate systems is the sliding concept. In the steam system, several operational paths are possible. Major control parameters for the steam system are pressure and temperature. In the control aspect, it is relatively difficult to simultaneously control both parameters with variation. Current power plants, including fossil fuel power plants, are operated by two distinct steam operation logics according to the operational modes. For lower power range, the recirculation mode is operated in the evaporator and/or steam generator. In the recirculation mode the steam generator receives recirculating water from the auxiliary tank, where the feedwater is mixed with the water separated from the saturated steam/water mixture, by means of a recirculation pump and sends the generated saturated steam/water mixture to the auxiliary tank. On the other hand, the once-through mode is operated for a higher power range. The once-through mode receives feedwater from the feedwater system and generates superheated steam which will be transferred to the steam header. The operational characteristics are nearly constant steam pressure for the recirculation mode and nearly constant steam temperature for the once-through mode, respectively. Here the terminology "nearly constant" means that the operating parameter can be slightly changed with respect to power changes.

There are some considerations about the once-through mode related to the characteristics of turbine operation. As mentioned before, the once-through mode has slightly variable steam temperature. Then a question on a steam pressure logic is raised. In general, the steam generator can generate steam at variable or constant pressure. The generated steam is transferred to the turbine through the common header. The turbine itself has its own operational characteristics independent of the steam pressure, e.g. the 1st stage impulse chamber pressure is mainly dependent on the steam flow rate which is proportional to the power level. This means that the steam pressure exerted from the steam generator does not have effect on the 1st stage pressure in the turbine. If the supplying pressure from the steam generator is larger than that of the turbine 1st stage, the excess pressure between the two pressure values should be exhausted by the turbine control valve. The pressure drop at the turbine control valve is energy loss and results in a reduced of plant thermal efficiency. Plant designers always try to minimize energy loss through the turbine control valve using concepts such as variable steam pressure. In addition to the benefit of efficiency, this concept also gives lower thermal transient to the turbine shell as shown in Fig. 5. Current fossil fuel power plants adopt this operational logic [9,10]. But in nuclear power plants, such operational logic can not be applicable because of the operating conditions in the primary and intermediate systems. During startup conditions, the plant is under recirculation mode and the primary and/or intermediate systems are maintained at relatively high temperature and whose corresponding saturated steam pressure is very high. In other words, the steam pressure is very high from the beginning of power operation range. This is why a constant high steam pressure logic is adopted for each plant mode in the nuclear power plants. In the fossil fuel power plant, the steam pressure can be relatively lower than that of the nuclear power plant during the early stage of the power operation range. This explains the differences in the typical trend of steam pressure operation logic between the nuclear power and the fossil fuel power plants.

The initial temperature of the primary and intermediate systems at zero power is assumed to be the average temperature of primary and intermediate cold temperatures. If the saturation temperature corresponding to the initial temperature of the primary and intermediate systems is greater than the nominal steam pressure, which is the case of KALIMER, the initial temperature is adjusted to the saturation temperature for the nominal steam pressure. As mentioned before, the switching power level from the recirculation mode to the superheated once-through mode is assumed to be at 25% power and the steam temperature is maintained constant as possible at the nominal values. The total flow through steam generator tube which is the sum of the recirculation flow and feedwater flowrate is maintained constantly during the recirculation mode. Nominal values of the KALIMER are assumed a reference condition and Fig. 6 shows the schematic diagram for the KALIMER heat balance at nominal condition. These are the assumptions in determining the KALIMER operation logic.

Now, the restraint condition is considered. KALIMER has passive negative reactivity insertion equipment called GEM (gas expansion module), which is filled with vessel cover gas before insertion into the core and this gas is compressed as the GEM is filled with sodium by the pressure from the primary pump. For all the power ranges, the GEMs should be filled with sodium using the primary pumps [1]. To do this all the primary pumps should be operating at least 90% of nominal condition. This is the restraint condition to the KALIMER operation logic.

2.4 Preliminary Operation Scheme

Using HSGSA-RE code, a preliminary operation scheme is obtained as shown in Fig. 7. As shown in Fig. 7, it is found that the steam temperature of the recirculation mode is dependent on the intermediate cold temperature or steam generator shell-side outlet temperature. On the other hand, in the case of the once-through mode the steam pressure is dependent on the intermediate hot temperature or the steam generator shell-side inlet temperature. This finding might be a useful guidance to be applicable when a steam control temperature control logic is set up for the plant control system. Fig. 7 shows large temperature differences in the intermediate hot and cold legs. To satisfy such large differences, the intermediate sodium flow rate should vary according to Fig. 8. As shown in Fig. 8, the intermediate sodium flow rate varies at 80% of the nominal flow rate from 25% to 100% power ranges. The large reduction of the sodium flow rate in the intermediate system will be apt to enhance the trend of thermal stratification in the pipe line, to reduce thermal heat transfer performance in the heat exchanger, such as the IHX (intermediate heat exchanger), and the steam generator due to reduced the Re number, and to interfere local thermal mixing in the steam generator shell side, which results in large temperature difference in the structures and structural damages [11]. To lessen these affects, the CRBR and the PRISM MOD-B have 35% and 50%, respectively, of the design flow as the lowest flow rates of the intermediate system. Considering these reference designs and a conservative approach, the KALIMER design temporarily adopts 50% of the nominal flow rate as the lowest sodium flow rate in the intermediate system. Due to the sodium flow rate change, a recalculation is conducted for the modified operation scheme and Fig. 9 shows the result for the temperature logic. Fig. 10 shows the flow rates of the primary, intermediate, and steam systems vs. power level. Figs. 9 and 10 represent reasonable features on the plant control logic. This control logic will be evaluated using a plant performance analysis computer code as further works to fix the plant control logic.

3. Conclusion

In the conceptual design of KALIMER, once-through helical coil steam generators are used to generate superheat steam. The once-through steam generator has its unique operational characteristics and a preliminary scheme for plant operation temperature. The operation temperature scheme determines typical thermal behaviors of the main systems in the plant and is the starting point in setting up the plant operation logic. Control features in plant operation between the PWR and LMR are discussed including several technical aspects that need to be considered in developing the plant operation logic. Using HSGSA-RE code, calculational results on the operation logic are obtained. Based on the results, a preliminary operation logic for KALIMER is proposed.

Acknowledgement

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Table 1. Comparison for power operation controls between PWR and LMR

Plant Type Parameter	PWR	LMR
Reactivity Control	Mainly Inherent on T_{avg}	Reactor Flux and Temperature
Flow Control	Full Flow	Nearly Full Primary Flow
Reactor T_{cold} Control	Constant High Primary Flow and Nearly Saturated Recirculation Flow	Variable Intermediate Flow and Feedwater Temperature
Feedwater Flow Control	Steam Generator Water Level and Power Level	Steam Pressure
Steam Temperature Control	Nearly Saturated (Inherent)	Superheated by way of Reactor Temperature
Turbine Control	Throttle	Throttle

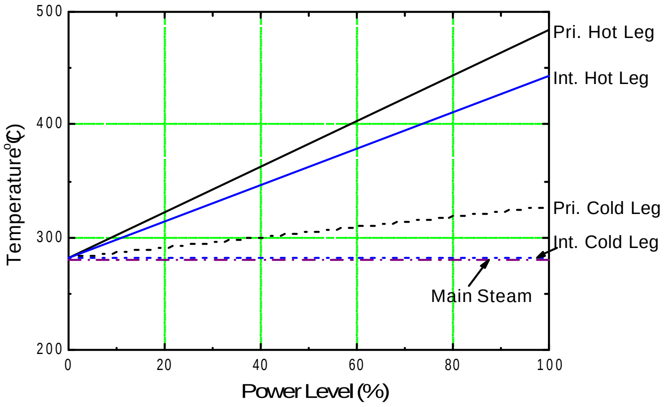


Fig.1 PRISM MOD-A Primary, Inrermediate, and Steam Operating Temperature

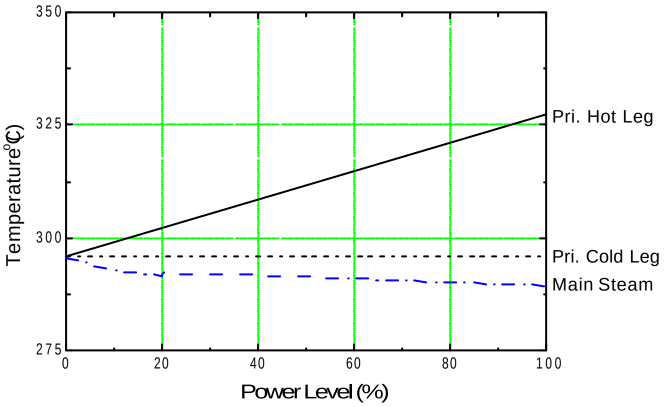


Fig.2 UCN 3,4 Primary and Steam Operating Temperature

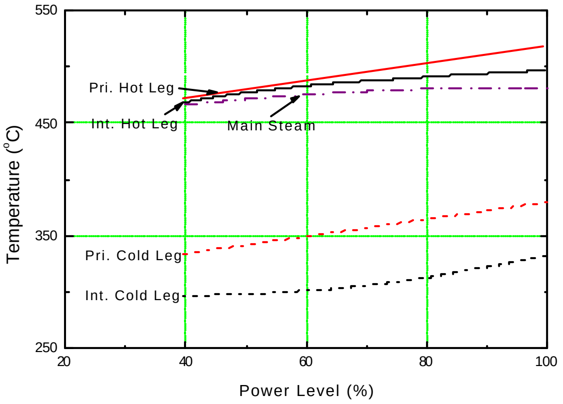


Fig.3 CRBR Primary, Intermediate, and Steam Operating Temperature

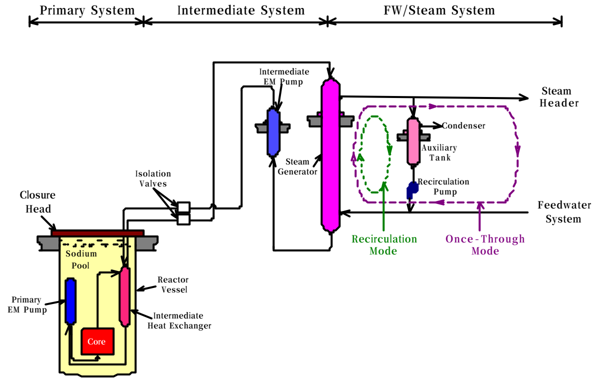


Fig. 4 Schematic Diagram of Operation Modes

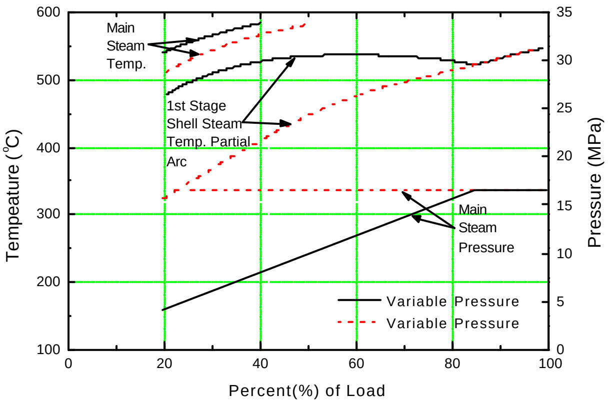
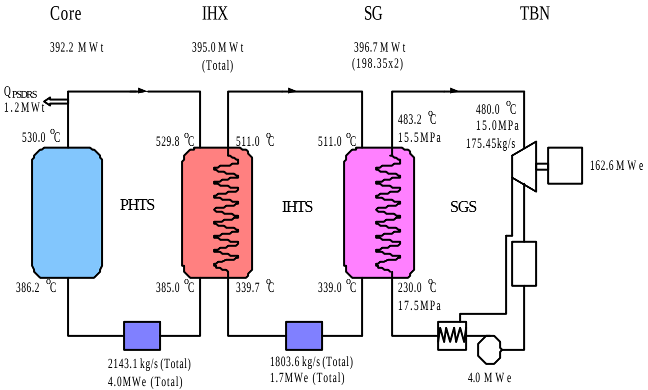


Fig.5 Example 1st-Stage Temperature vs. Load/Variable Pressure Operation Compared with Constant Pressure Operation



- Net Plant Power = 150MWe
- Gross Efficiency= 41.5%
- Net Efficiency = 38.2%

Fig. 6 KALIMER Plant Heat Balance at Full Power

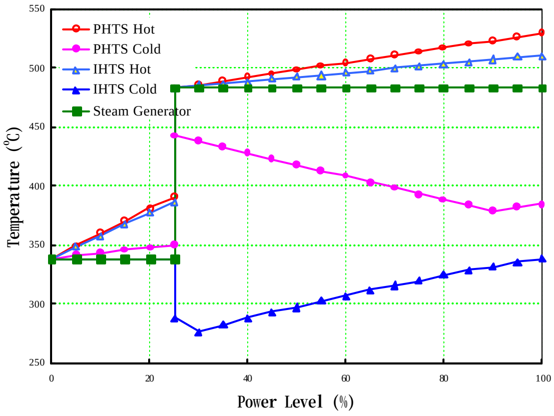


Fig. 7 Calculated Operational Temperature Logic

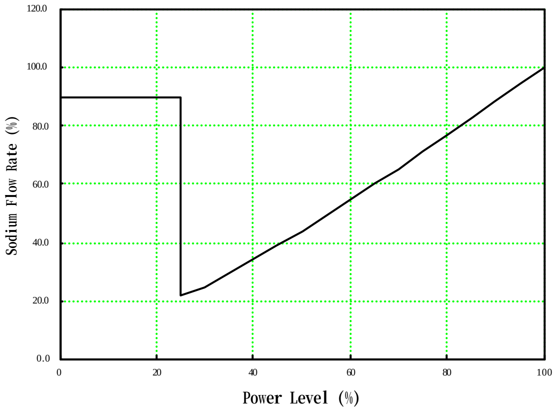


Fig. 8 Intermediate sodium flowrate vs power.

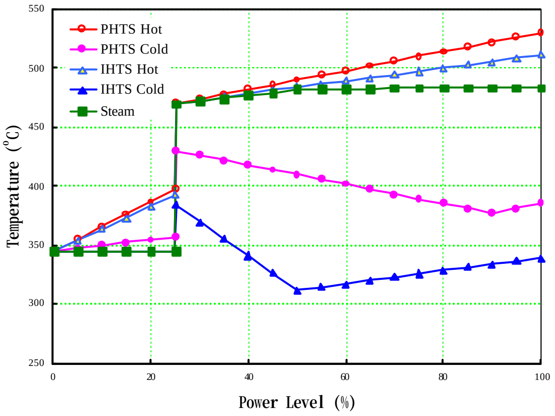


Fig. 9 KALIMER's Operational Temperature Concept

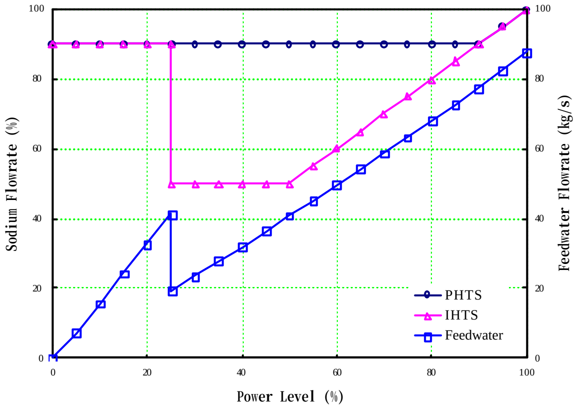


Fig. 10 Primary/Intermediate Sodium and Feedwater Flowrate vs Power