DEVELOPMENT OF A SIMPLIFIED MODEL FOR ANALYZING THE PERFORMANCE OF KALIMER-600 COUPLED WITH A SUPERCRITICAL CARBON DIOXIDE BRAYTON ENERGY CONVERSION CYCLE

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A KALIMER-600 concept which is a type of sodium-cooled fast reactor, has been developed at KAERI. It uses sodium as a primary coolant and is a pool-type reactor to enhance safety. Also, a supercritical carbon dioxide (CO_2) Brayton cycle is considered as an alternative to an energy conversion system to eliminate the sodium water reaction and to improve efficiency. In this study, a simplified model for analyzing the thermodynamic performance of the KALIMER-600 coupled with a supercritical CO_2 Brayton cycle was developed. To develop the analysis model, a commercial modular modeling system (MMS) was adopted as a base engine, which was developed by nHance Technology in USA. It has a convenient graphical user interface and many component modules to model the plant. A new user library for thermodynamic properties of sodium and supercritical CO_2 was developed and attached to the MMS. In addition, some component modules in the MMS were modified to be appropriate for analysis of the KALIMER-600 coupled with the supercritical CO_2 cycle. Then, a simplified performance analysis code was developed by modeling the KALIMER-600 plant with the modified MMS. After evaluating the developed code with each component data and a steady state of the plant, a simple power reduction and recovery event was evaluated. The results showed an achievable capability for a performance analysis code. The developed code will be used to develop the operational strategy and some control logics for the operation of the KALIMER-600 with a supercritical CO_2 Brayton cycle after further studies of analyzing various operational events.

KEYWORDS : KALIMER-600, Supercritical CO_2 Brayton Cycle, Performance Analysis, MMS

1. INTRODUCTION

A sodium-cooled fast reactor (SFR) concept called the Korea Advanced Liquid Metal Reactor with 600-MW electricity (KALIMER-600) has been developed at KAERI. It is a pool-type reactor and uses sodium as the coolant in the primary and intermediate loops. The supercritical carbon dioxide (CO_2) Brayton energy conversion cycle is considered as an alternative for the power conversion system. Comparing to the conventional Rankine steam cycle, the supercritical CO_2 Brayton cycle has a higher cycle efficiency and can save capital cost with smaller and fewer components. Moreover, it can eliminate the probability of a sodium water reaction in a steam generator, which is one of the most important safety issues of a SFR. So, it can be a promising alternative to the Rankine steam cycle for a SFR. The supercritical CO_2 and sodium have different thermo-physical behaviors compared to those of an ideal gas and water. The currently available performance analyzers cannot solve the thermodynamic behaviors of KALIMER-600 coupled with a supercritical CO_2 Brayton cycle because they don't have the thermodynamic properties of supercritical CO_2 and sodium. Therefore, a new performance analysis code is needed to adequately address the specific features of the supercritical CO_2 Brayton energy conversion cycle coupled to the KALIMER-600. [1,2]

In this work, a simplified model for the performance analysis code for the KALIMER-600 with a supercritical CO_2 Brayton energy conversion cycle has been developed. To develop the performance analysis, a commercial modular modeling system (MMS) code was adopted as a base solver for the flow and energy of the system, which was developed by nHance Technology in the USA. The MMS is a MS-Windows based visual and modular software system for modeling the dynamic characteristics of a power plant system and for studying various design, performance and operation aspects. Component modules in the MMS code have been developed in order to represent the mechanical or control components in the actual plant and the interface specifications can be defined so that the modules could be interconnected analogously to the components. Otherwise, it has lots of control and mechanical modules such as a PID controller, pipe, pump, turbine and fuel (core) modules, and those modules can be connected to one another to analyze the integral thermodynamic behaviors of a plant. Also, it provides a comfortable graphical user interface based on an MS-windows system. Therefore, it is easy to model the plant or to modify a model according to a change in plant design. [3]

The library for the thermodynamic properties of the sodium and the supercritical CO_2 was developed and then attached as an additional user library to the original MMS code, because the original MMS code did not have them. [4,5] In addition, some component modules such as the fuel and pipehx were modified to be adequate for the KALIMER-600 coupled with a supercritical CO_2 Brayton cycle. After modifying some component modules and adopting the properties of the sodium and the supercritical CO_2 as a property library of the MMS code, a simplified performance analysis code for KALIMER-600 with a supercritical CO_2 Brayton cycle was developed.

A steady state and a simple power reduction and recovery event were analyzed by using the developed code. From the steady state analysis, the adequacy of the developed model was evaluated and the transient thermodynamic behavior of the plant was analyzed through a simple power reduction and recovery event. It was concluded that the model had a good capability to analyze a steady state and a transient event such as a power reduction and recovery event and some data would be used in developing control logics. Finally it will be used to develop the strategy of the operation, control and monitoring for a KALIMER-600 coupled with a supercritical CO_2 Brayton cycle through further analyses of various operational events.

2. KALIMER-600 COUPLED WITH SUPERCRITICAL CARBON DIOXIDE BRAYTON CYCLE

The KALIMER-600 has two heat transport systems, namely the PHTS (Primary Heat Transport System) and IHTS (Intermediate Heat Transport System). Also, a supercritical CO_2 Brayton energy conversion cycle is considered as an alternative to the Rankine cycle for the balance of plant (BOP) system. The PHTS is a pool type system and this feature provides a large thermal inertia of the primary system that enhances the plant safety. The IHTS consists of two loops and each loop has its own heat exchanger to BOP system and related systems. The core heat in the PHTS is transferred to the IHTS by way of the intermediate heat exchangers (IHXs) and then

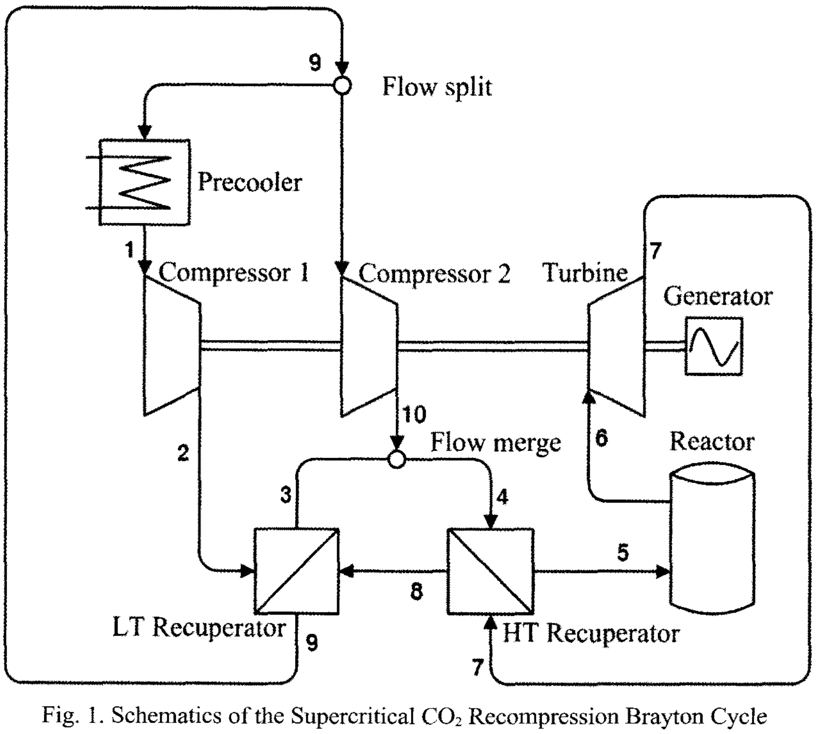


Fig. 1. Schematics of the Supercritical CO_2 Recompression Brayton Cycle

transferred to the Brayton cycle through Na-CO_2 heat exchangers (HEX). The IHX uses a conventional shell-and-tube heat exchanger but the heat exchangers in the supercritical CO_2 Brayton cycle are composed of printed circuit heat exchanger (PCHE) types in order to increase the economy with a smaller size than a shell-and-tube heat exchanger. [2]

As an advanced power conversion system, the supercritical CO_2 Brayton cycle has many advantages. It has a good efficiency at a modest temperature, a simplified compressor design and compact size of the heat exchangers and turbines. Moreover, the supercritical CO_2 Brayton cycle coupled to the KALIMER-600 excludes the possibilities of a sodium water reaction, which is one of the most important safety-related issues. The recompression supercritical CO_2 Brayton cycle is adopted, which has two compressors to avoid the inverse temperature difference in the inlet of the compressor due to a drastic variation of the specific heat of the supercritical CO_2 near the critical point. Figure 1 shows the schematic diagram of the supercritical CO_2 recompression Brayton cycle.[2]

The temperature-entropy (T-s) diagram of the recompression supercritical CO_2 Brayton cycle is depicted in Figure 2.[2] In the recompression Brayton cycle, two recuperators (i.e., regenerative heat exchangers) are used for the utilization of the remaining supercritical CO_2 thermal energy in the cycle and the minimization of the discharged heat in the cooler can be achieved with the second compressor (points 9-10). Therefore, the split fraction of the flow for the direction to the cooler and the compressor is a significant design parameter. The compressor inlet temperature (point 1 in Figure 2) is set to 31.25°C, near to the critical point of supercritical CO_2 (7.377MPa and 30.97°C) for maximizing the cycle efficiency. The flow-split ratio at a downstream of the low temperature recuperator (LTR) was determined from the preliminary analysis of a correlation between the heat transfer area of the LTR and the cycle efficiency. The flow-split ratio for the direction to the cooler and the compressor was assigned as 71% and 29%, respectively. Figure 3 shows the heat balance of the KALIMER-600 coupled with a supercritical CO_2 Brayton cycle. [2] In Figure 3, the Eff. means the efficiency of the plant and the Ef. means the effectiveness of a heat exchanger.

When establishing a heat balance between the PHTS and IHTS, the required design parameters were adopted from the conceptual design data of the KALIMER-600 coupled with a Rankine cycle. The parameters were the Na-CO_2 HEX temperature and the pressure of the supercritical CO_2 side of the Brayton cycle, the compression works, net electric power output, pump efficiencies, inlet and outlet temperature of the core, and system pressure drop.[1] The temperature distribution of the IHTS, which is important to establish a heat balance, was determined in order to minimize the heat-transfer areas of the IHX and Na-CO_2 HEX. Table 1 shows the assumed data of the efficiency of each component for establishing a heat balance for a rated full power operation.

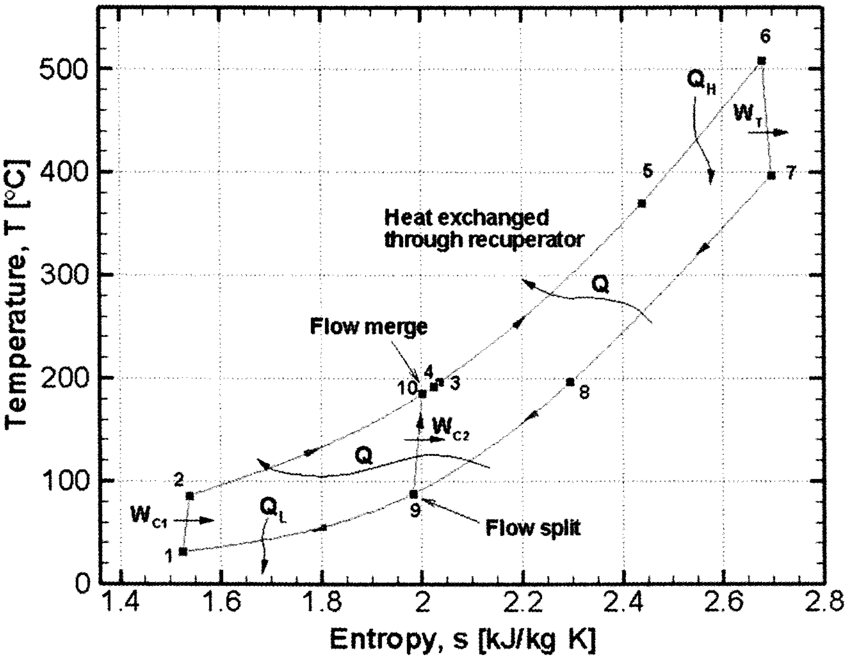


Fig. 2. T-s Diagram of the Recompression Supercritical CO_2 Brayton Cycle

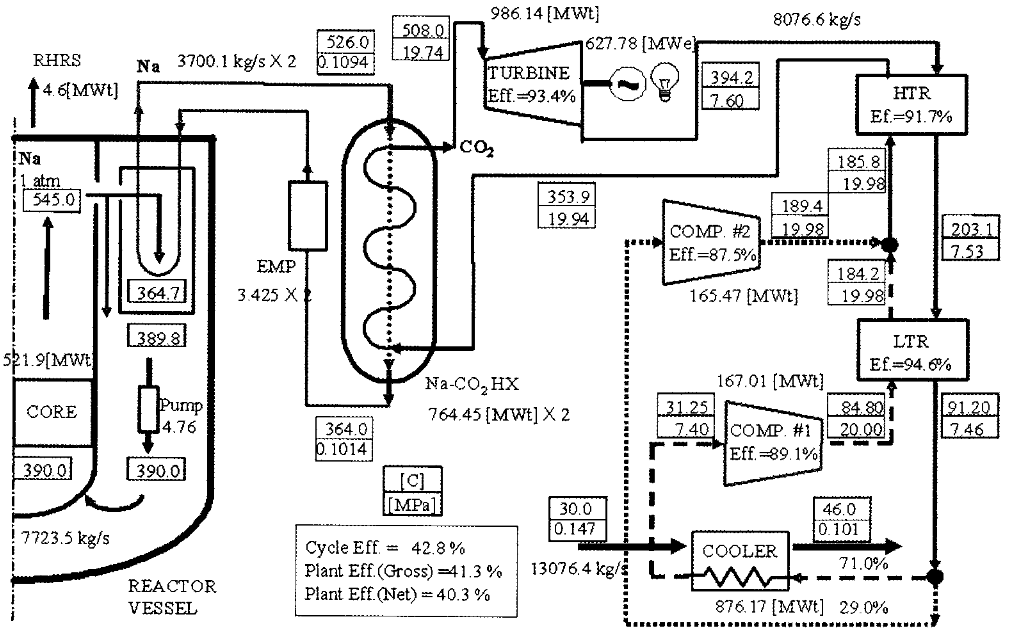


Fig. 3. Heat Balance of KALIMER-600 Coupled with Supercritical CO_2 Brayton Cycle

Table 1. Assumption Data for Efficiency of each Component

System	Component	value
Supercritical CO_2 Brayton Cycle	Turbine efficiency [%]	93
	Compressor 1 efficiency [%]	89
	Compressor 2 efficiency [%]	87
	HTR effectiveness [%]	92
	LTR effectiveness [%]	95
	LTR downstream flow-split ratio [%:%]	71 : 29
PHTS and IHTS	PHTS pump efficiency [%]	85
	IHTS pump efficiency [%]	50
	PHTS heat loss [%]	0.3

3. FEATURES OF MMS

The MMS has lots of advantageous features when developing a performance analysis code for a power plant. It has a convenient graphical user interface based on the MS-Windows operating system and a capability to minimize the user input by an auto-parameterization function which can calculate the thermodynamic parameters of each component model required for simulating a transient status of the plant from the steady state calculation. It has a lot of component modules which can be used for analyzing a plant such as pipe, pump, pipehx, turbine and fuel (core) modules and those modules can be connected to each other to analyze the transient behaviors of the plant. Moreover, these modules can be modified by using user-supplied ACSL (Advanced Continuous Simulation Language) codes in a macro file or FORTRAN routines in order to represent some plant-specific components. It has some control components such as a PID control module to express a control action and it can analyze the transient behaviors of a plant in a real time according to the control actions. Therefore, the MMS was adopted as a base engine to develop a simplified performance analysis code for the KALIMER-600 coupled with a supercritical CO_2 Brayton cycle. Figure 4 shows the general procedure for developing a performance analysis code using the MMS code.

However, the MMS code does not have any thermodynamic properties for sodium and supercritical CO_2 as an internal property library. Those are required in order to model the sodium loop and the supercritical CO_2 cycle of a KALIMER-600 because the MMS code had been developed for the conventional plants using water or various gases. [3,6] An additional user library of the thermodynamic properties for sodium and supercritical CO_2 was developed and attached to the original MMS code.

In addition, some modules internally provided by the MMS code were modified to be adequate for SFR components. The fuel module and pipehx module were significantly modified and then the modified MMS code was named the MMS-LMR (liquid metal reactor) code.

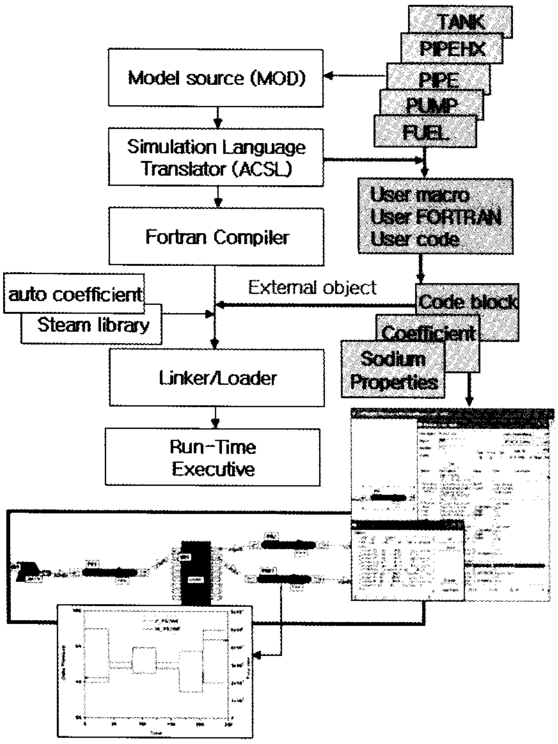


Fig. 4. Procedures for Developing MMS Code

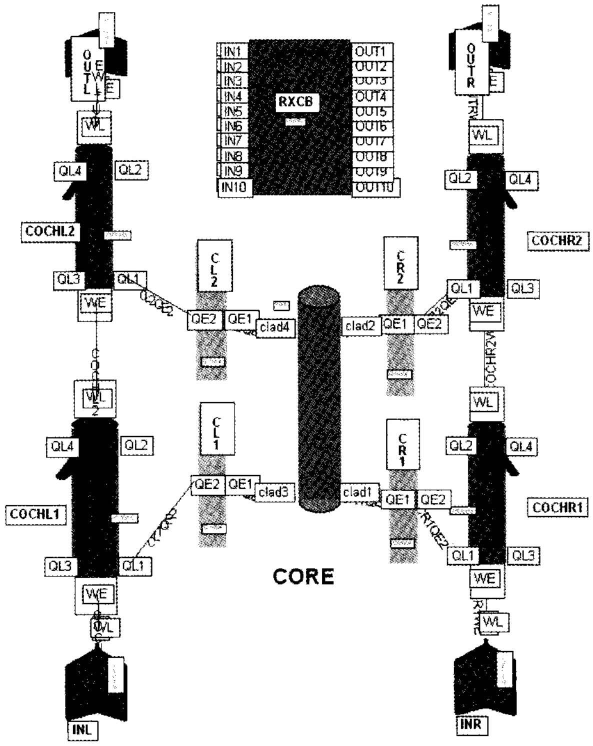


Fig. 5. Core Model of KALIMER-600

The fuel module is used to model the kinetics of a lumped reactor and the pipehx module is used to analyze the heat transfer between a heat structure and a fluid by convection. The shadowed box in Figure 4 shows the modified features to attach the sodium properties and the modified macros for the MMS-LMR code.

3.1 Fuel Module for KALIMER-600

The fuel module represents multiple fuel nodes (typically 4 nodes) in a nuclear reactor and can calculate the reactor thermal power by using the point kinetic model of each node. It originally has a 6 delayed neutron group model, a 3 decay heat group model, an Iodine-Xenon chain model, a Moderator Temperature Model (MTC), and a Doppler coefficient model. The calculated thermal power is distributed into the fuel nodes and connected to the moderator or coolant volumes according to the user-provided fraction of the energy deposition. The nuclear fuel cladding and moderator are simulated outside this module by a separate "Qmetal" module which is a kind of heat structure module and pipehx modules which can simulate the heat transfer between metal (clad) and coolant. So, a combination of the fuel, Qmetal, and pipehx modules can model the dynamic behavior of a core by flow/energy solver and a point kinetic equation. The point kinetic model calculates the reactivity feedback effect of a coolant and fuel assemblies by analyzing the heat transfer between the fuel and the coolant.

Figure 5 shows a general core model in the MMS-LMR code using the fuel, Qmetal, and pipehx modules. The Qmetal module connected to the fuel modules has only one pipehx module because a fuel module can simulate the thermal power of the core without a pipehx module which can simulate the flow and heat transfer of a coolant. The pipehx modules with a heat transfer correlation between the rod bundles and the primary sodium are described in section 3.2. The reactivity worth of control rods can be modeled as a user subroutine in a code block of the MMS-LMR code, which can represent some user-supplied control parameters for evaluating some characteristics in the MMS-LMR code. The RXCB CODE block in the figure 5 should be programmed by a user in order to calculate the reactivity worth for the control rods at a given location, and it can simulate the control rod programming with the control rod worth table and operation strategy related to the temperature program of the coolant according to the power level.

The fuel module in the MMS code has been developed for a typical core of a PWR plant. However, a KALIMER-600 core has some different features in the reactivity model compared to the MTC model and the Doppler model in a PWR. It also has a different poisoning effect of the poison materials like Xenon due to the fast neutron spectrum and the characteristics of the metal fuel used in a KALIMER-600 core. The reactivity model was changed to be suitable to the KALIMER-600 core. At first, the MTC model was changed to a reactivity change model which comes from the sodium density change in the coolant. The coefficient table and the reactivity table were obtained through the safety analysis result of the KALIMER-600. [7] The reactivity model due to a change of the sodium density can be expressed by the following equation.

$$d\rho_{density} = a\,\frac{\rho_{Na}(T_i) - \rho_{Na}(T_{ref})}{\rho_{Na}(T_{ref})} \tag{1}$$

Where,

$d\rho_{density}$ = *reactivity change due to sodium density change,*
$a = 2.5818 \times 10^{-4}$(*coefficient for KALIMER*-600 *core*).
$\rho_{Na}(T_i)$ = *sodium density at sodium temperature* T_i,
$\rho_{Na}(T_{ref})$ = *sodium density at reference temperature* T_{ref} (=467.5°C) *of sodium*

The Doppler model was also changed for the KALIMER-600 core with fast neutron spectrum and metal fuel assembly as the following:

$$d\rho_{Doppler} = \rho_i - \rho_0 \tag{2}$$

Where

$d\rho_{Doppler}$ = *reactivity change due to Doppler model*
$\rho_i = bT_i^{-0.12}$ (*Doppler reactivity at fuel temperature* T_i *in KALIMER*-600 *core*),
$\rho_o = bT_{ref}^{-0.12}$ (*reference Doppler reactivity in KALIMER*-600 *core*),
$b = 0.1020975$ (*coefficient for KALIMER*-600 *core*),
$T_{ref} = 370.9$ *°C (reference temperature for Doppler model of KALIMER*-600 *core*).

The reactivity change due to the density change of the poisoning materials like Xenon was ignored because the absorption cross section of the poison materials were negligible at the fast neutron spectrum of KALIMER-600.

As shown in Figure 5, a fuel module can represent a lumped core with a reactivity model, 4 Qmetal modules can model the cladding material and 4 pipehx modules can express the coolant fluid in the core. The fuel is internally divided into 4 nodes which represent the axial and radial lumped power distributions of the core. Each node is connected to each Qmetal and pipehx module. Each connection can solve the reactivity and thermal power of a fuel. Table 2 shows some of the core characteristics with the reactivity value of a nominal thermal power (100% full-rated power) in the KALIMER-600 core.

3.2 Pipehx Module for KALIMER-600

The pipehx module can represent a section of piping with a heat transfer mechanism between a metal and a fluid connected by a Qmetal module. A heat exchanger can be modeled by two pipehx modules coupled with a Qmetal module with the appropriate heat transfer correlations. Figure 6 shows a typical model for the heat

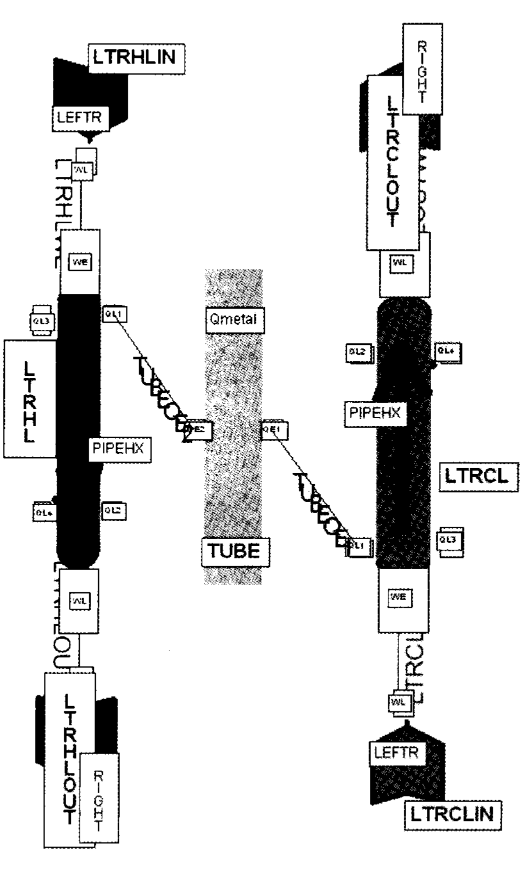


Fig. 6. Typical Heat Exchanger Model

Table 2. Core Characteristics in Nominal Condition

Component	variables	Reference value	Analysis value	Error (%)
Core	Flow rate [kg/s]	7723.5	7730.5	0.09
	Temperature inlet/outlet [°C]	545.0/390.0	545.3/390.3	0.06/0.08
	Power [MW]	1521.9	1523.4	0.10

exchanger. Various heat exchangers such as the intermediate heat exchanger (IHX), Na-CO_2 heat exchangers (HEX), and recuperators in the PHTS, IHTS loop, and the supercritical CO_2 cycle were modeled in this way. For the simulation of heat transfer between a heat structure and a flow of sodium or supercritical CO_2, several heat transfer correlations related to a sodium flow were newly implemented into the MMS-LMR code. Modified Schad correlation was applied in the rod bundle region in the core and the Graber-Rieger correlation was implemented for the sodium of the IHX shell side. [7] For the inside of a pipe or tube in the IHX, the Aoki model was applied. [7]

- *Modified Schad*

$$Nu = \left[-16.15 + 24.96\left(\frac{P}{D}\right) - 8.55\left(\frac{P}{D}\right)^2\right] Pe^{0.3} \tag{3}$$

- *Graber-Rieger*

$$Nu = 0.25 + 6.2\left(\frac{P}{D}\right) + \left[0.032\left(\frac{P}{D}\right) - 0.007\right] Pe^{0.8-0.024\frac{P}{D}} \tag{4}$$

- *Aoki correlation*

$$Nu = 6.0 + 0.025\left[0.014\,\mathrm{Re}^{1.45}\,\mathrm{Pr}^{1.2}\left(1 - \frac{e^{-71.8}}{\mathrm{Re}^{0.45}\,\mathrm{Pr}^{0.2}}\right)\right]^{0.8} \tag{5}$$

Where,

Nu = *Nussult number,*
Pe = *Peclet number,*
Re = *Reynolds number,*
Pr = *Prandlt number,*
$\left(\frac{P}{D}\right)$ = *pitch to diameter.*

For the heat transfer for the supercritical CO_2 Brayton cycle, the Hesselgreaves correlation was implemented for the supercritical CO_2 side of all the heat exchangers of the Brayton cycle. [2] For the sodium side of the Na-CO_2 HEX, the Lockart-Martinelli correlation was used. [2]

- *Hesselgreaves*

$$\begin{aligned} Nu &= 4.089 && \textit{for } \mathrm{Re} \le 2300 \\ Nu &= 4.089 + \frac{Nu_{\mathrm{Re}=5000} - 4.089}{5000 - 2300}(\mathrm{Re} - 2300) && \textit{for } 2300 < \mathrm{Re} < 5000 \\ Nu &= 0.125\,\mathrm{Re}^{0.64}\,\mathrm{Pr}^{0.33} && \textit{for } 5000 \le \mathrm{Re} \end{aligned} \tag{6}$$

- *Lockart-Martinelli*

$$Nu = 5.0 + 0.025(\mathrm{Re\,Pr})^{0.8} \tag{7}$$

With pipehx module and Qmetal module, the heat exchanger models like IHX, Na-CO_2 HEX and two recuperators (HTR, LTR) were produced. Each heat exchanger was verified using the design (steady) data for

Table 3. Verification of each Heat Exchanger Model

Component	variables	Reference value	Analysis value	Error (%)
IHX	Flow rate [kg/s] shell/tube	7723.5/7400.2	7735.9/7401.8	0.16/0.02
	Temperature inlet/outlet [°C] Shell side	545.0/389.8	545.1/389.9	0.02/0.02
	Temperature inlet/outlet [°C] tube side	526.0/364.0	525.9/364.1	0.02/0.03
	Total heat transfer rate [MW]	1528.7	1527.7	0.07
Na-CO_2 HEX	Flow rate [kg/s] sodium/supercritical CO_2	7400.2/8076.6	7400.2/8084.8	0.0/0.1
	Temperature inlet/outlet [°C] sodium channel	526.0/364.0	526.1/363.9	0.02/0.0
	Temperature inlet/outlet [°C] supercritical CO_2 channel	508.0/353.9	507.9/353.9	0.02/0.0
	Total heat transfer rate [MW]	1528.7	1529.9	0.08
HTR	Flow rate [kg/s] Hot channel/cold channel	8076.6/8076.6	8070.5/8085.9	0.08/0.1
	Temperature inlet/outlet [°C] hot channel	394.2/203.1	394.1/202.8	0.03/0.14
	Temperature inlet/outlet [°C] cold channel	353.9/185.8	354.7/185.9	0.23/0.05
	Total heat transfer rate [MW]	1746.6	1753.9	0.42
LTR	Flow rate [kg/s] Hot channel/cold channel	8076.6/5734.4	8100.4/5731.9	0.29/0.04
	Temperature inlet/outlet [°C] hot channel	203.1/91.2	203.1/91.4	0.0/0.22
	Temperature inlet/outlet [°C] cold channel	184.2/84.8	184.9/84.8	0.38/0.0
	Total heat transfer rate [MW]	1070.3	1076.1	0.54

KALIMER-600 coupled with supercritical CO_2 cycle. Table 3 shows the verification results between design data and analysis results. The results show good agreement between the developed models and the design data.

4. DEVELOPMENT OF THE ANALYSIS CODE FOR KALIMER-600

Using the MMS-LMR modules, a performance analysis code for the KALIMER-600 with a supercritical CO_2 Brayton cycle was developed. It consists of models for PHTS, IHTS, and the supercritical CO_2 Brayton cycle. [1,2] The models are composed of the reactor, various pipes, IHX, and the Na-CO_2 HEX, HTR, and LTR as previously mentioned..

Since a gas turbine for a supercritical CO_2 cycle has not been designed in detail yet, the turbine was assumed as a heat sink in this model. The Na-CO_2 cycle was modeled separately and, finally, linked to the PHTS/IHTS model. For simplicity, the cooler in the supercritical CO_2 Brayton cycle was assumed to be an ideal cooler which could always produce the same thermodynamic condition at the exit of the supercritical CO_2 side in the cooler during any transient condition of the plant. This means the cooler outlet condition in supercritical CO_2 side is always the same condition (7.4MPa and 31.25°C) under any operational condition.

5. ANALYSIS RESULTS

5.1 Steady State Analysis

For evaluating the accuracy of the model including the geometric data and the thermodynamic properties of the coolant with the flow rate and the distributions of the temperature in the loops, the steady-state of the KALIMER-600 was analyzed and verified with heat balance data. The detailed geometric and thermodynamic data for the steady state analysis are given in reference 1. Table 4 shows the results of the steady state calculation for a rated full power operational condition.

Since the detailed specification of the components and piping arrangement for a supercritical CO_2 Brayton cycle have not been completed yet, some characteristics of the performance like the compressors and pipe layouts in the cycle, were assumed. Therefore, the analysis results show a small difference between the reference values and the calculated values. Especially, the supercritical CO_2 thermodynamic properties through compressor #2 show some errors. It was assumed that this could be easily overcome with a detailed design of the supercritical CO_2 cycle later. Therefore, it was supposed that the results showed an achievable agreement between the reference values and the analysis data.

5.2 A Power Reduction and Recovery Event

Using the developed code, a simple power reduction and recovery event was studied. With this analysis, it was possible to evaluate some characteristics of the thermodynamic parameters during a transient state of the KALIMER-600. It could be used to develop a control and operation strategy later. Since the detailed design of the gas turbine for a supercritical CO_2 cycle have not been specified yet, the thermodynamic behaviors of the KALIMER-600 according to the turbine power reduction

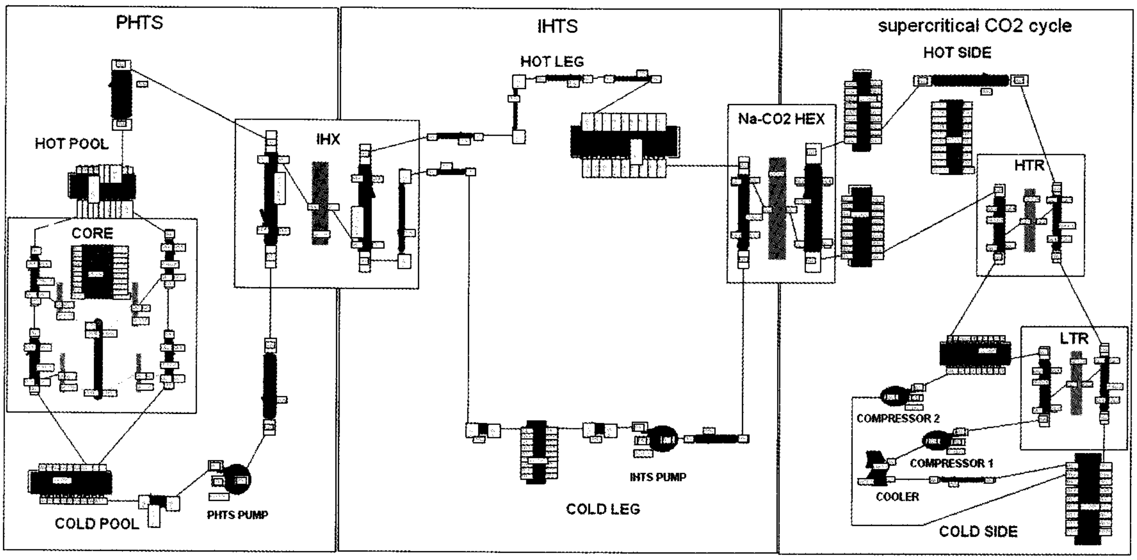


Fig. 7. A Simplified Performance Analysis Model for KALIMER-600 with Supercritical CO_2 Brayton Cycle

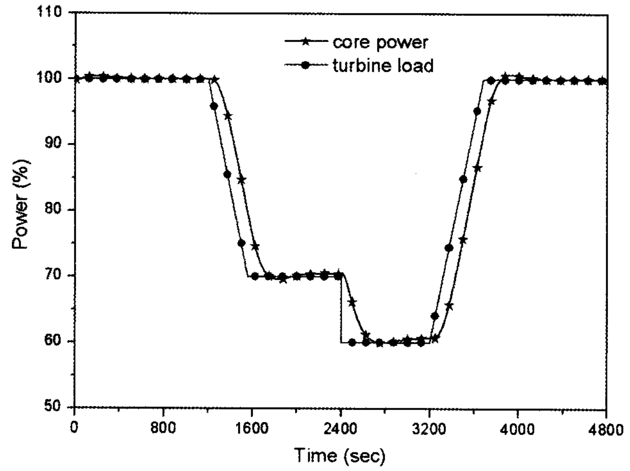
were only examined by decreasing the heat removal rate through the turbine. That is to say, the system behavior was examined according to a change of the thermal condition of the plant when the rate of the heat removal through the turbine was decreased without changing the flow rate in the supercritical CO_2 Brayton cycle. The assumed ramp rate of the power increase or decrease was 5 %/min and the assumed step change of the power was 10 % of the full rated power. In this study, an ideal cooler was assumed, which meant the outlet condition in the CO_2 side of the cooler was always fixed at a pressure of 7.4MPa and a temperature of 31.25°C during any transient state.

The results of the transient analysis are shown in Figure 8. A postulated 70% power reducing event with a ramp rate of 5 %/min was evaluated. The turbine load was reduced to 70% with a ramp rate of 5 %/min and then the 70% power level was maintained for the next 1200 seconds. The core power was stabilized at 70.5% after a little delay. After that, the turbine load was dropped to 60% by a 10% step change, and it was maintained for the next 800 seconds. The core power was predicted to be 60.6%. In the last stage, the turbine load was recovered to the rated full power with a ramp rate of 5 %/min. In this case, no control rod movement was assumed because the control rod programming following operational strategy of the primary temperature and flow with a power change have not yet been developed. It will be developed later based on the operational strategy developed by using this analysis code. So, the core power only resulted from the characteristics of the thermodynamic behaviors and the reactivity feedback from the temperature of PHTS loop.

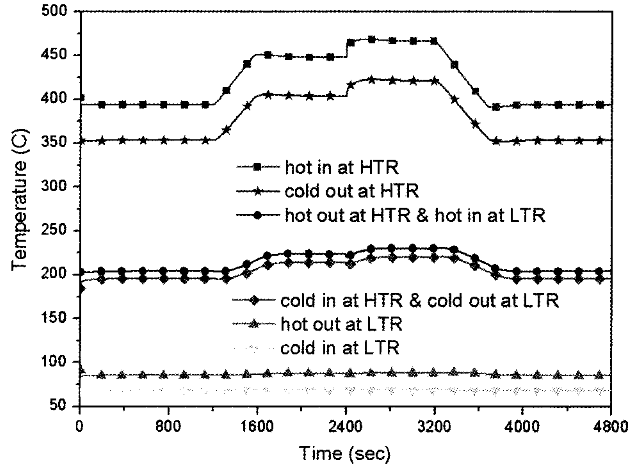
The core power followed the turbine power of the supercritical CO_2 cycle through the developed reactivity feedback models of the core. The process of the change of the core power is as follows. At first, the inlet temperature in the supercritical CO_2 side of the Na-CO_2 HEX was increased because of a reduction of the heat removal rate through the turbine of the supercritical CO_2 cycle and then the temperature in the IHTS cold leg was increased following the temperature change of the CO_2 cycle. There

Table 4. Summary of Steady State Calculation

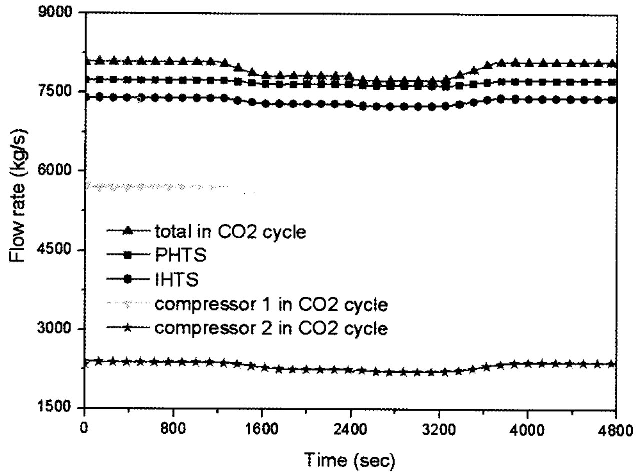
Parameters	reference	result	Error (%)
Reactor Power (%)	100	100.08	0.08
Temperature at core inlet/outlet [°C]	390/545	390.2/545.3	0.05/0.06
PHTS flow rate (kg/s)	7723.5	7732.5	0.16
Temperature at IHX inlet/outlet in IHTS [°C]	364.0/526.0	364.1/526.1	0.03/0.02
IHTS flow rate	7400.2	7401.9	0.02
Temp. at Na-CO_2 PCHE in Brayton cycle [°C]	353.8/508	353.9/508	0.03/0.0
Temperature at turbine outlet [°C]	394.2	394.8	0.15
Temperature at HTR [°C]			
Hot channel inlet/outlet	394.2/203.1	394.8/204.9	0.15/0.89
Cold channel inlet/outlet	185.8/353.9	192.6/353.8	3.66/0.03
Temperature at LTR [°C]			
Hot channel inlet/outlet	203.1/91.20	204.9/85.6	0.89/6.14
Cold channel inlet/outlet	84.8/184.2	68.2/167.8	19.6/8.9
Pressure at LTR [MPa]			
Hot channel inlet/outlet	7.6/7.53	7.59/7.46	0.13/0.93
Cold channel inlet/outlet	19.98/19.94	19.83/19.79	0.75/0.75
Pressure at LTR [MPa]			
Hot channel inlet/outlet	7.53/7.46	7.46/7.4	0.93/0.80
Cold channel inlet/outlet	20.0/19.98	19.85/19.83	0.75/0.75
Flow rate in Brayton cycle [kg/s]			
Total	8076.6	8076.7	0.0
Compressor 1	5734.42	5707.0	0.48
Compressor 2	2342.21	2369.8	1.18



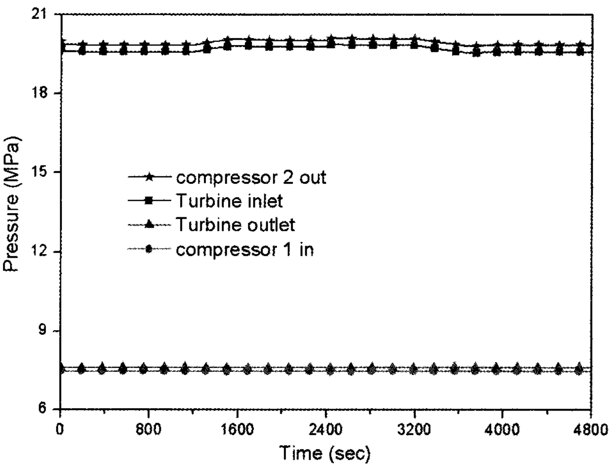
(a) Power Level and Turbine Load



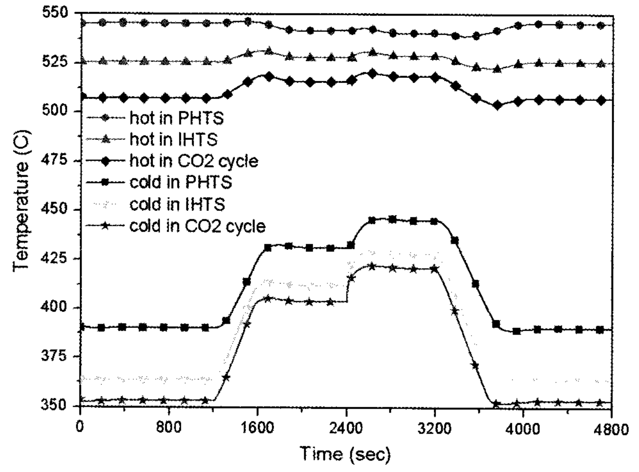
(d) Temperature in Supercritical CO_2 cycle



(b) Flow Rate of Plant



(e) Pressure in Supercritical CO_2 Cycle



(c) Temperature of Plant

Fig. 8. Results of Transient State Calculation

was some time delay due to a difference of the thermal capacity between the IHTS loop and the supercritical CO_2 cycle. Accordingly, the temperature of the cold leg in the PHTS loop was increased. The increase in the PHTS temperature causes the sodium density and the fuel temperature to change which result in the insertion of negative reactivity into the core. Finally, the core power followed the turbine power (heat removal rate) and the amount of power reduction in the core was the same as that of the load rejection (heat removal rate) of the supercritical CO_2 Brayton cycle. The results indicated that the MMS-LMR code has a reasonable capability to simulate the transient behaviors of a KALIMER-600 plant coupled with a supercritical CO_2 Brayton cycle despite not having a real turbine and cooler model.

As shown in Figure 8, the flow rate and pressure condition of the event were slightly changed because the density of the fluid was affected by the change of the temperature distribution. The temperature distribution was significantly changed because the heat removal rate through the turbine was changed as previously mentioned. This resulted in a change of the core power to follow the change of the heat removal rate in the supercritical CO_2 Brayton cycle. This feature shows the core power could be maneuvered by only the reactivity feedback with temperature of the core. In a real plant, the temperature of the PHTS, IHTS and turbine cycle should be maintained within a certain range according to the temperature program. So, the control rod should move to meet the reactivity change of the core following the change of the turbine load. The temperature program and control rod programming will be developed through various operational transients.

The PHTS of a KALIMER-600 is a large pool comparing to the IHTS and supercritical CO_2 Brayton cycle and this large quantity of coolant can function as an energy buffer. That is to say, the coolant medium can temporarily absorb the discordance between the power of the core and the turbine during a load-following operation. Thus, a time delay exists between the turbine load and the core power and gives a sufficient margin for the control rod programming. In this study, the time delay and time constant to decrease or increase the power of the core and the turbine were studied. The delay originates from the large thermal capacity of PHTS loop which can absorb some transient situations. The delay will be used to develop a control strategy for the KALIMER-600 through further studies. In this study, it was assumed that the reactivity of the core was changed instantaneously from the temperature change of the PHTS loop and the fuel assembly.

From Figure 8, the power and temperature behaviors were identified and the delay time could be calculated. The delay time of the temperature change between the inlet of the Na-CO_2 HEX and the inlet of the IHX was about 30 seconds and it was about 60 seconds between the inlet of the Na-CO_2 HEX and the inlet of the core. There are two kinds of time delay between the turbine side and the primary system when considering the plant behaviors and control strategies. The first is the transfer time of thermodynamic parameters from the turbine load to the core through the Na-CO_2 HEX, IHX and PHTS/IHTS loop and the other is a measurement delay. The first was about 90 seconds, which was obtained through the analysis. Due to the large coolant inventory between the core and the turbine, the coolant temperature information arrived at the core from the supercritical CO_2 cycle with a considerable delay. However, any measurement delay was not considered in this study and these will be dealt with in further studies.

Also, the overshooting of the change of the core power was evaluated to be about 0.8% and it could be used when developing a control strategy of the plant to minimize the stability problem. In addition, the time constant of the core power change including the time delay through the PHTS and IHTS loop was evaluated and it was found during the 10% step change of the turbine power at 2400 second in this analysis. The time constant of the change of the core power which originated from the change of the heat removal rate of turbine was about 148 seconds.

After finalizing the turbine and cooler model, the measurement delays and time constants of the sensors to measure the thermodynamic characteristics such as the temperature, flow rate and, core power will be considered. Time constant and time delay data will be used to develop an operational strategy and control program for a change of the core power and the turbine load of a KALIMER-600 for a stable operation with maximized efficiency of the plant operation later.

6. CONCLUSIONS

A simplified performance analysis code for the KALIMER-600 coupled with a supercritical CO_2 Brayton cycle was developed by using the MMS-LMR code developed in this study. The developed model was verified through an analysis of the design data of each component modeling and a steady state calculation with a rated full power condition of the KALIMER-600 with a supercritical CO_2 Brayton cycle. Then, a simple power reduction and recovery event was analyzed. The results showed that the developed code can satisfactorily simulate the reactivity change of the core and the transient status of the plant. Also, some useful data for designing the control strategy of the plant were obtained.

After developing an appropriate turbine model with a power control algorithm and a cooler component including a supporting mechanism, the code will be used to analyze plant performance and to develop an optimal control logic for the operation of KALIMER-600 with a supercritical CO_2 Brayton cycle through further studies of analyzing various operational events.

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