DEVELOPMENT OF A SUPERCRITICAL CO₂ BRAYTON ENERGY CONVERSION SYSTEM COUPLED WITH A SODIUM COOLED FAST REACTOR

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Systematic research has been conducted by KAERI to develop a supercritical carbon dioxide Brayton cycle energy conversion system coupled with a sodium cooled fast reactor. For the development of the supercritical CO₂ Brayton cycle ECS, KAERI researched four major fields, separately. For the system development, computer codes were developed to design and analyze the supercritical CO₂ Brayton cycle ECS coupled with the KALIMER-600. Computer codes were developed to design and analyze the performance of the major components such as the turbomachinery and the high compactness PCHE heat exchanger. Three dimensional flow analysis was conducted to evaluate their performance. A new configuration for a PCHE heat exchanger was developed by using flow analysis, which showed a very small pressure loss compared with a previous PCHE while maintaining its heat transfer rate. Transient characteristics for the supercritical CO₂ Brayton cycle coupled with KALIMER-600 were also analyzed using the developed computer codes. A Na-CO₂ pressure boundary failure accident was analyzed with a computer code that included a developed model for the Na-CO₂ chemical reaction phenomena. The MMS-LMR code was developed to analyze the system transient and control logic. On the basis of the code, the system behavior was analyzed when a turbine load was changed. This paper contains the current research overview of the supercritical CO₂ Brayton cycle coupled to the KALIMER-600 as an alternative energy conversion system.

KEYWORDS : Supercritical CO₂, Brayton Cycle, Energy Conversion System, SFR, KALIMER-600, PCHE

1. INTRODUCTION

A sodium cooled fast reactor, which is a candidate for the next generation reactor, has had a traditional Rankine cycle as its energy conversion system up to now. Recently, the research on the power cycle for the next generation reactor has been conducted and the supercritical CO₂ Brayton cycle has been presented as a promising alternative to the current Rankine cycle. The supercritical CO₂ Brayton cycle provides improved plant efficiencies relative to the gas recuperated (e.g., helium) considering Brayton cycles and Rankine steam cycles operating at the same reactor core outlet temperatures and core power levels. The high fluid density of supercritical CO₂ remarkably reduces the size of turbine and compressors, resulting in significant reductions in the size and capital cost of the turbomachinery. Dostal et. al. [1,2] have proposed the use of such a cycle and have calculated that cycle efficiencies as high as 45 percent might be achieved using a recompression cycle in

which half of the flow passes through a heat sink precooler and in which the supercritical CO₂ is heated by the reactor to temperatures as high as 550 °C. The reduced component size makes it possible to reduce the size of the turbine generator building. JAEA preliminarily estimated the size of the reactor building. Compared with a conventional SFR system that has a secondary sodium circuit and a steam cycle system, the size of the SFR that adopts an S-CO₂ system is reduced by approximately 20% [3]. From the cost reduction of component size and turbine building, the expected cost reduction of electricity generation seems to be more than 7~8% of total construction cost of the nuclear power plant. As the design is in a preliminary stage, further study is needed for a more detailed estimation.

The Korea Atomic Energy Research Institute (KAERI) has conducted systematic research to develop supercritical CO₂ Brayton cycle energy conversion systems and to evaluate their performance when they are coupled to advanced nuclear reactor concepts of the type investigated

in the Generation IV Nuclear Energy Systems Initiative (e.g., Sodium cooled Fast Reactor, Lead cooled Fast Reactor, Very High Temperature Reactor). KAERI has researched four major activities, separately.

For the system development, computer codes were developed to calculate the heat balance of various power operation conditions in which all component models were incorporated. Based on the computer codes, the supercritical CO₂ Brayton cycle energy conversion system was constructed for the sodium fast reactor concept, KALIMER-600 (pool type reactor, 600MWe).

In order to develop the supercritical CO₂ turbomachinery models, design codes for the turbomachinery, such as an axial turbine and a radial type compressor, were developed. Based on the design codes, the design parameters were prepared to configure the KALIMER-600 S-CO₂ turbomachinery models. The models were evaluated by means of both expert consultations and thermo-hydraulic analysis with the help of a commercial CFD code. Through the models, off-design characteristics and the sensitivities of the supercritical CO₂ turbomachinery were investigated.

To enhance safety and economics, various kinds of heat exchangers were investigated. Since the Printed Circuit Heat Exchanger™ (PCHE™) [4] is the only compact exchanger that offers parent metal strength and properties throughout the entire exchanger owing to its diffusion bonding technology, the PCHE was selected for the supercritical CO₂ Brayton cycle energy conversion system. For the evaluation of diffusion-bonded heat exchangers similar to PCHE models, a one-dimensional analysis computer code was developed to evaluate the performance of the heat exchangers and design data for the typical PCHE was produced.

In parallel with the PCHE-type heat exchanger design, a diffusion-bonded airfoil shape fin heat exchanger has been newly designed. The new design concept was evaluated by three-dimensional CFD analyses, which have showed that the airfoil shape fin heat exchangers conserve the total heat transfer rate and reduce the pressure drop by a factor of 14. The diffusion-bonded airfoil shape fin heat exchanger has a special feature that could change fin density more freely in a fluid channel and control the thermo-hydraulic characteristics in the HX.

Possible control schemes for power control in the KALIMER-600 supercritical CO₂ Brayton cycle were investigated by using the MARS code. The MMS-LMR code was also developed to analyze the transient phenomena in an SFR with a supercritical CO₂ Brayton cycle. The results of the MMS-LMR code were compared with the heat balance for the given component data and the MARS-LMR analysis results. A simple power/load reduction and recovery event was selected for the transient calculation. Then, the transient behavior was analyzed for the KALIMER-600 supercritical CO₂ Brayton cycle.

The S-CO₂ Brayton cycle energy conversion system coupled with an SFR is also very attractive from the

aspect that it can achieve a more reliable system design completely free from the essential risk of the sodium-water reaction (SWR) phenomenon possibly occurring in a conventional Rankine cycle energy conversion system. Although this novel approach will yield significant improvements in overall plant energy utilization, it raises issues regarding the consequences of heat exchanger boundary failure, resulting in an intermixing of CO₂ and liquid sodium.

For the evaluation of the Na-CO₂ boundary failure event, a computer code was developed to simulate the complex thermodynamic behaviors of the chemical reaction between liquid sodium and CO₂ gas. The long term behavior of a Na-CO₂ boundary failure event and its consequences, which lead to a system pressure transient, were evaluated for the shell-and-tube type Na-CO₂ heat exchanger of the KALIMER-600 employing a supercritical CO₂ Brayton cycle.

This paper describes the current research status for a supercritical CO₂ Brayton cycle coupled to the KALIMER-600 as an alternative energy conversion system.

2. SUPERCRITICAL CO₂ BRAYTON CYCLE ENERGY CONVERSION SYSTEM

2.1 Normal Operation Conditions of the KALIMER-600 System

In order to establish normal operating conditions for the KALIMER-600 supercritical CO₂ Brayton cycle energy conversion system, two major codes were developed, namely the design computer codes "DENOP" and "RECOBA". The design code DENOP plays the role of calculating the heat balance between the primary heat transport system (PHTS) and the intermediate heat transport system (IHTS). The RECOBA code was used to calculate the heat balance of the S-CO₂ Brayton cycle ECS, which was developed on the basis of references [1,5,6]. The properties of the S-CO₂ were calculated by using the subroutine REPROP program of the NIST [7].

The recompression S-CO₂ Brayton cycle, which has two compressors, was adopted to avoid the inverse temperature difference in the inlet of the compressor, which is due to a drastic variation of the specific heat of supercritical CO₂ near the critical point. In the recompression Brayton cycle, the minimization of the discharged heat in the cooler can be achieved with a second compressor. Therefore, the split fraction of the flow is a significant design parameter. Two recuperators (i.e., regenerative heat exchangers) are used for the utilization of the remaining supercritical CO₂ thermal energy in the cycle. The compressor inlet temperature is set to around 31.25 °C, near the critical point of CO₂ (static pressure 7.377 MPa, static temperature 30.97 °C), for the maximization of the cycle efficiency [8]. Figure 1 shows normal operating conditions of the KALIMER-600 S-CO₂ Brayton cycle

energy conversion system, which adopts two recuperators and two compressors.

To establish normal operating conditions, the total reactor system is composed of a primary heat transport system (PHTS), an intermediate heat transport system (IHTS), and a supercritical CO₂ Brayton cycle as an energy conversion system (ECS). Systems are interconnected with heat exchanging system for energy transfer. The core heat in the PHTS is transferred to the IHTS by way of the intermediate heat exchangers and then transferred to the Brayton cycle through the Na-CO₂ heat exchangers (HX). Supercritical CO₂ gas of high pressure and temperature is used to operate the turbine system and generate electrical energy through an expansion process. The primary and intermediate heat transport system of the KALIMER-600 Rankine cycle was used to establish normal operating conditions for the KALIMER-600 S-CO₂ Brayton cycle. Thus, the IHTS heat of the KALIMER-600 reactor (1528.9 MWt) was transferred to the power conversion system of the Brayton cycle through the Na-CO₂ HX. While the thermal balance between the PHTS and the IHTS was calculated by using the DENOP, that between the IHTS and Brayton cycle was established by the RECOBA code.

To establish a thermal balance between the PHTS and the IHTS, the required design parameters such as the Na-CO₂ HX temperature and pressure of the side of the S-CO₂ Brayton cycle, the compression works, the net electric power output, the pump efficiencies, the inlet and outlet temperatures of the core, and the system pressure drop

were adopted from those values for the KALIMER-600 Rankine cycle [9]. The temperature distribution of the IHTS, which is important in establishing a thermal balance, was determined in order to minimize the heat-transfer areas of the IHX and Na-CO₂ HX and to simultaneously approach the effectiveness of the HX. The input values for the analysis of the thermal balance are summarized in Table 1, in which the isentropic efficiencies were used for the S-CO₂ turbomachinery.

In order to establish a thermal balance in the Brayton cycle, design parameters such as the inlet and outlet temperatures and cycle's effectiveness for Na-CO₂ HX, the efficiencies of the turbine and compressors, and the flow-split ratio in the downstream of the low temperature recuperator (LTR) are required. In this analysis, the exit temperature of the Na-CO₂ HX was assigned as 508 °C, which was determined in order to limit the maximum heat-transfer tube length to within 11 m for the shell and the tube type heat exchanger. The efficiencies of the turbine and the two compressors and the effectiveness of the LTR and HTR were calculated based on the conceptual design of the components, since there is no reference value up to now. The flow-split ratio at the downstream of the LTR was determined from the preliminary analysis of the correlation between the heat transfer area of the LTR and the cycle efficiency. The flow-split ratio of the directions to the cooler and to the compressor were assigned at 71% and 29%, respectively. The reason for these figures is explained in the following section.

Fig. 1. Normal Operating Condition of the S-CO₂ Brayton Cycle Coupled to the KALIMER-600

Table 1. Input Data for Establishing a Normal Operating Condition

item	Input parameter	unit	KALIMER-600
Brayton Cycle thermal balance	Na-CO ₂ HEX heat transfer rate	[MW _i]	1528.9
	Na-CO ₂ HEX exit temperature	[°C]	508.0
	Turbine efficiency	[%]	93.4
	Compressor 1 efficiency	[%]	89.1
	Compressor 2 efficiency	[%]	87.5
	HTR effectiveness	[%]	91.7
	LTR effectiveness	[%]	94.6
	LTR downstream flow-split ratio	[-]	71 : 29
PHTS and IHTS thermal balance	Na-CO ₂ HEX heat transfer rate	[MW _i]	1528.9
	Net electric power output	[MW _e]	627.78
	Core outlet temperature	[°C]	545.0
	Core inlet temperature	[°C]	390.0
	PHTS system pressure drop	[MPa]	0.45
	IHTS system pressure drop	[MPa]	0.40
	PHTS pump efficiency	[%]	85
	IHTS pump efficiency	[%]	50
	PHTS heat loss	[%]	0.3
	Na-CO ₂ HEX CO ₂ inlet temperature	[°C]	353.9
	Na-CO ₂ HEX CO ₂ outlet temperature	[°C]	508.0
	Na-CO ₂ HEX CO ₂ outlet pressure	[MPa]	19.74
	Na-CO ₂ HEX CO ₂ heat-transfer tube pressure drop	[MPa]	0.2
	Compression work	[MW]	332.48

2.2 Estimation of the Flow-Split Rate at the LTR Downstream

As mentioned previously, the flow-split ratio of the downstream LTR and the heat-transfer area of the LTR have effects on the cycle efficiency. Using the RECOBA code, the factors such as the cycle efficiency of the Brayton cycle, the overall heat transfer rate (UA) of the HTR and LTR, and the ΔT_{LMTD} were calculated along a variation of the flow-split ratio.

As shown in Figure 2, the system efficiency tends to decrease linearly and the heat-transfer area of the HTR slightly decreases when the cooler-side split flow is increasing. However, the heat-transfer area of the LTR considerably increases up to 69% and then it gradually decreases. When we observed a wide range of the split mass fraction, the trace of cycle efficiency tended to increase parabolically with the decrease of the split mass fraction, which has a maximum value in the vicinity of 65%, and then it tended to decrease.

Table 2 shows the cycle efficiency and the heat-transfer

Fig. 2. Cycle Efficiency, UA and ΔT_{LMTD} of a LTR and a HTR for the Flow-split Ratio of a LTR Downstream

Table 2. Cycle Efficiency and Heat-transfer Area with a Flow-split Ratio at Downstream from the LTR

Flow-split ratio [%]	65	69	70	71
Cycle efficiency [%]	43.8	43.1	42.9	42.8
Heat-transfer area of LTR [m ²]	263868.9	96429.2	83465.7	73969.3
Area ratio for the 65% flow-split ratio	1	0.365	0.316	0.280

Fig. 3. Specific Diameter and Specific Speed with the Compressor Type

area of the LTR with a split-flow ratio (65%, 69%, 70%, and 71%). Although the cycle efficiency shows the maximum when the split-flow ratio is 65% at the cooler-side, the length of the flow-path was estimated to exceed the manufacturing limit of the PCHE. When the split-flow ratio was 71%, the area of the LTR considerably decreased to 28% of the area of the 65% flow ratio, although the efficiency decreased by only 1%. Considering the cycle efficiency and the area in the PCHE, the flow-split ratio for the cooler-side was determined at 71%.

3. PRELIMINARY DESIGN OF MAJOR COMPONENTS AND FLOW ANALYSIS

3.1 Design of Supercritical CO₂ Compressor

The efficiencies of the turbine and compressor are important parameters for the S-CO₂ energy conversion cycle. Since there is no practical experience of S-CO₂ turbomachinery related with the Brayton cycle, it is necessary to establish the methodology for the design and performance analysis before the detailed design and manufacturing stage.

The development process for a compressor can be roughly divided into conceptual design, preliminary design,

detailed design, and performance evaluation. In the conceptual design, the compressor type is previously determined together with the overall size from the characteristic diagram of Barber-Nichols Inc. seen in Figure 3 [10]. The contour line in the diagram indicates the same efficiency according to compressor type. After this, the specific speed and the specific diameter are roughly selected, and the compressor type is iteratively determined to maximize the efficiency by tuning the specific speed N_s and the specific diameter D_s in Equation (1).

$$N_s = \frac{N\sqrt{V_f}}{H^{3/4}}, \quad D_s = \frac{DH^{1/4}}{\sqrt{V_f}} \quad (1)$$

where N is the rotation number of the compressor (rpm), D is the diameter (ft), H is the head (ft), and V_f is the volume flow rate (ft³/s).

A conceptual design of the two compressors for the KALIMER-600 Brayton cycle was conducted by using the above methodology. The design parameters are summarized in Table 3 for the conceptual design of the two centrifugal compressors. The parameters such as the averaged density, the rotational speed, and the volume

Table 3. Conceptual Design Parameters of the Compressor

	Unit	Compressor 1	Compressor 2
Average density	kg/m ³	466.3	200.8
Stage pressure difference	MPa	6.3	4.2
Stage head	m	1377.8	2119.3
Rotational speed	rpm	3600	3600
Diameter	ft	2.95	2.63
Volume flow rate	(ft ³ /s)	434.33	411.92
Specific speed	-	136.09	95.96
Specific diameter	-	1.16	1.18
Stage		2	3

Table 4. Loss Model Summary of the Centrifugal Compressor

Loss mechanism		Loss model
Internal loss	Incidence loss	Conrad et.al (1980)
	Blade loading loss	Coppage et. al (1956)
	Skin friction loss	Jansen (1967)
	Clearance loss	Jansen (1967)
Diffuser loss	Mixing loss	Johnston and Dean (1966)
	Vaneless diffuser loss	Stanitz (1952)
External loss	Disk friction loss	Daily and Nece (1960)
	Recirculation loss	Jansen (1967)
	Leakage loss	Aungier (1955)

flow rate were determined from the operation conditions; the maximum diameter and the head of the compressor were determined to maximize the efficiency, as seen in the diagram for the specific diameter and the specific speed.

As a result of the iterative calculations, and based on the design parameters in Table 3, the stages of the two compressors (Compressor 1, Compressor 2) were determined as two and three, respectively. From Figure 3, the efficiency of the compressor was estimated during the process of the conceptual design to be more than 80% for the S-CO₂ Brayton cycle coupled to the KALIMER-600. The diameter was estimated to be within 1 m for the two compressors.

The performance analysis code, named COMP1D, for a centrifugal compressor for the S-CO₂ cycle, was developed on the basis of the meanline analysis method, which is a one-dimensional analysis method. Since a sensitive loss model is required in order to include the effect of the impeller configuration and the flow path parameter, the loss model suggested by Oh was used to develop the code [11]. Performance analysis of the centrifugal compressor

Fig. 4. Performance Characteristics of Compressor 1 for the Off-design-points **Fig. 5.** Performance Characteristics of Compressor 2 for the Off-design-points

Table 5. Design Parameter of Compressor 1

Compressor 1	Stage [ea]	Rotation [rpm]	Mass Flow Rate [kg/s]	P _{in} [MPa]	T _{in} [°C]	P _{out} [MPa]
	2	3600	5730	7.40	31.3	20.0
1 st stage [m][deg]	Inlet tip diameter	Inlet hub diameter	Out diameter	Outlet width	Blade number	Axial length
	0.72	0.1	1.28	0.21	18	0.7
	Inlet tip angle	Inlet hub angle	Outlet blade angle	Diffuser diameter	Clearance	
	63	52	75.5	1.68	0.004	
2 nd stage [m][deg]	Inlet tip diameter	Inlet hub diameter	Out diameter	Outlet width	Blade number	Axial length
	0.68	0.1	1.26	0.20	17	0.65
	Inlet tip angle	Inlet hub angle	Outlet blade angle	Diffuser diameter	Clearance	
	72	55	76	1.2	0.003	

Table 6. Design Parameter of Compressor 2

Compressor 1	Stage [ea]	Rotation [rpm]	Mass Flow Rate [kg/s]	P _{in} [MPa]	T _{in} [°C]	P _{out} [MPa]
	3	3600	2342.22	7.46	91.2	20.0
1 st stage [m][deg]	Inlet tip diameter	Inlet hub diameter	Out diameter	Outlet width	Blade number	Axial length
	0.47	0.08	1.39	0.14	13	0.48
	Inlet tip angle	Inlet hub angle	Outlet blade angle	Diffuser diameter	Clearance	
	53	41	55	1.313	0.004	
2 nd stage [m][deg]	Inlet tip diameter	Inlet hub diameter	Out diameter	Outlet width	Blade number	Axial length
	0.46	0.08	1.31	0.13	13	0.44
	Inlet tip angle	Inlet hub angle	Outlet blade angle	Diffuser diameter	Clearance	
	58	45	57	1.213	0.004	
3 rd stage [m][deg]	Inlet tip diameter	Inlet hub diameter	Out diameter	Outlet width	Blade number	Axial length
	0.435	0.08	1.21	0.12	13	0.42
	Inlet tip angle	Inlet hub angle	Outlet blade angle	Diffuser diameter	Clearance	
	61	48	57.5	1.11	0.004	

was conducted with the COMP1D code on the basis of the loss model described in Table 4.

One-dimensional design data were also calculated with the help of the COMP1D code, which was developed to determine compressor configuration parameters at the 100% nominal point. Table 5 and Table 6 are the design data of compressor 1 and compressor 2, respectively. Using these data, three-dimensional compressor configurations could be generated before the CFD analysis. More details on the one-dimensional design code, COMP1D, are found in reference [12].

Figure 4 shows the characteristics of the off-design performance of compressor 1 in the range of 50%~130% of the mass flow rate of 5734.41 kg/s, and in the range of 40%~120% of the rotational speed of 3600 rpm at the

operating point. For the analysis, the inlet condition and the outlet condition were given as P_{inlet}=7.4 MPa, T_{inlet}=31.3 °C and P_{outlet}=20 MPa, respectively. The characteristic curves in the figure show the maximum efficiency at the design point and the pressure ratio 2.7 as a design requirement.

Using the COMP1D code, performance analysis was also conducted for compressor 2 with the same method. Figure 5 shows the characteristics of the off-design point of compressor 2 at the condition of a mass flow rate of 2342.22 kg/s and a rotational speed of 3600 rpm at the operating point. For the analysis of compressor 2, the inlet condition and the outlet condition were given as P_{inlet}=7.46 MPa, T_{inlet}=91.2 °C and P_{outlet}=20 MPa, respectively. It is estimated that the difference of the efficiency characteristics originates from the different operation

Fig. 6. Design Point of Turbine in the Diagram of the Specific Diameter and Specific Speed

conditions between the two compressors. Since compressor 1 is operated near the critical point, the properties inside it varied greatly.

3.2 Design of Supercritical CO₂ Turbine

The S- CO₂ turbine was conceptually designed by using a similar process and methodology to that applied to the compressor design. Table 7 shows the major design factors that were used to perform the conceptual design of the turbine for the S-CO₂ Brayton cycle coupled to the KALIMER-600 reactor. A one-dimensional design code, named TURBID, was developed to analyze the performance of the S- CO₂ turbine at an operation point. The design code for the S-CO₂ turbine was developed on the basis of references [5,13,14]. In addition to the losses associated with the blades, secondary losses also exist, including those due to leakage of fluid flow between the tips of the blades and the casing of the turbine. In the code, secondary loss due to leakage between the tips and the casing was assumed to be 5%.

Preliminary performance analysis of the turbine was conducted for the S-CO₂ Brayton cycle coupled to the KALIMER-600 reactor. A sensitivity analysis for the performance parameters was conducted by using the TURBID code.

The off-design performance and sensitivity analysis for the turbine was conducted by using the TURBID code, which was modified slightly to evaluate the sensitivity of the parameters. For the calculation, the inlet condition was given as $P_{inlet}=20$ MPa, $T_{inlet}=550$ °C and the outlet

Table 7. One-dimensional Design Data of Turbine

	Unit	4 Stages	3 Stages
Average density	kg/m ³	97.4	97.4
Stage pressure difference	MPa	3.04	4.05
Stage head	m	3178	4237
Rotational speed	rpm	3600	3600
Diameter	ft	5.3	5.6
Volume flow rate	ft ³ /s	2928.9	2928.9
Specific speed	-	188.8	152.2
Specific diameter	-	0.98	1.12
Stage		4	3

condition as $P_{outlet}=7.4$ MPa, respectively. The permissible blade stress was assumed to be 300 MPa.

Figure 7 shows an efficiency change according to the stage number and the hub diameter of the turbine. By increasing the stage number, the efficiency of the turbine tends to increase and approach a constant value. Hub diameter efficiency tends to increase linearly. However, since an increment of the hub diameter results in a cost increase for the turbine due to volume enlargement, the hub diameter should be determined at a proper size to optimize its efficiency.

Figure 8 shows the blade angle variation for the stage

Fig. 7. Sensitivity Analysis of the S-CO₂ Turbine Efficiency for the Stage Number and Hub Diameter

Fig. 8. Sensitivity Analysis of the S-CO₂ Turbine Blade Angle for the Stage Number and Hub Diameter

number and the hub diameter of the turbine. The blade angle was increased linearly with the stage number and the hub diameter. Compared with the STAR-LM blade angle of ANL [5,8,15,16], the value is large, at approximately 10~20 degrees, which is estimated from the difference of the flow rate. For a change of the blade angle, the efficiency should be checked to find an optimum combination for the stage number and the hub diameter. Since the blade exit angle was dependent on the loss model in the current method, the Soderberg loss model needs to be modified to reduce the uncertainty of the conceptual design of the turbine.

3.3 Flow Analysis Supercritical CO₂ Turbine and Compressor

The off-design performance of the KALIMER-600 S-CO₂ turbine was also estimated with three-dimensional CFD analysis. The commercial ANSYS CFX-11 code was used to conduct the flow analysis of the S-CO₂ turbine. For the CFD analysis, the properties of the supercritical CO₂ were calculated on the basis of the NIST property program and were then inserted in the CFX solver as the RGP(Real Gas Property) table.

The basic design parameters and detailed information on the shape of the turbine in the KALIMER-600 are presented in Table 8. Three dimensional configuration of the S-CO₂ turbine was generated by ANSYS BladeGenTM as shown in Figure 9. The boundary conditions consisted of the S-CO₂ Brayton cycle energy conversion system for the KALIMER-600, as presented in Table 9.

From the CFD analysis, the efficiency of the turbine

Table 8. Three-dimensional Design Parameters of the KALIMER-600 S-CO₂ Turbine for the CFD Analysis

Parameters		
First stage	Sator	Rotor
Hub radius [cm]	53	
Shroud radius [cm]	69~70	70~71
Chord radius [cm]	7.2	
Blade angle [°]	60~67	
Second stage	Sator	Rotor
Hub radius [cm]	55	
Shroud radius [cm]	72.5~73.5	73.5~74.5
Chord radius [cm]	7.8	
Blade angle [°]	60~67	
Third stage	Sator	Rotor
Hub radius [cm]	57	
Shroud radius [cm]	76~77	77~78
Chord radius [cm]	8.4	
Blade angle [°]	60~67	
Fourth stage	Sator	Rotor
Hub radius [cm]	59	
Shroud radius [cm]	79.5~80.5	80.5~81.5
Chord radius [cm]	9	
Blade angle [°]	60~67	
Number of blades [#]	40

Fig. 9. Three Dimensional Shape of the S-CO₂ Turbine for the KALIMER-600**Table 9.** Information on the Grids and Boundary Conditions

Grids	
Number of Stator and Rotor Grids [#]	1,098,048 (137,256)
Hub to Shroud Distribution Parameter_End Ratio [-]	200
O-Grid_End Ratio [-]	50 (200)
O-Grid Distance Factor [-]	0.1 (inflation: 10)
Topology	H-J-L Grid
Total Number of Hexahedrons [#]	1,020,096 (127,521)
Boundary Conditions	
Inlet Total Temperature [K]	787
Inlet Total Pressure [MPa]	20
Outlet Static Pressure [MPa]	7.6
S-CO ₂ Properties	NIST properties
Turbulence Model	Shear Stress Transport

reaches around 85 %; the mass flow reaches 8800 kg/s at the pressure ratio of 2.25 and maintains a constant value for the higher pressure ratio, as show Figure 10. These results are slightly different from the value in the one-dimensional design data which seems to come from the difference of fluid properties and loss models. The one-dimensional design code was developed based on the properties of compressed air, but the fluid of this system is compressed CO₂.

Figure 11 shows a configuration of turbomachinery for the KALIMER-600 S-CO₂ Brayton cycle energy conversion system. To evaluate the performance of the compressor, compressor 2 was analyzed by the ANSYS-CFX code, as shown in Figure 12, in which a change of the efficiency and pressure ratio were depicted with the mass flow rate. The efficiency of the compressor has a maximum value of 95% at the half of a design mass flow rate. This value deviates to some extent from the design value, which has a maximum efficiency of 87.5% at a design mass flow rate.

Fig. 10. S-CO₂ Turbine Performance Curves (Design Point, Pr=2.75)

Fig. 11. Turbomachinery Configuration for the KALIEMR-600 Brayton Cycle Energy Conversion System

From the CFD analysis, it seems that the difference between the one-dimensional data and the CFD analysis data comes from the lack of real material, such as a loss model for the S-CO₂ turbomachinery in the vicinity of the critical point and experiences.

3.4 Design of Supercritical CO₂ Heat Exchanger and Flow Analysis

For the design of the heat exchanger, a one-dimensional analysis code has been developed to evaluate the heat

transfer performance and pressure drop characteristics of the PCHE. In order to assess the applicability of the developed model, the calculated results were compared with the published experimental data. For this purpose, three reference data bases for the PCHE were collected [17~21]. Using the available correlations of heat transfer coefficient and friction factor, the experimental data were evaluated. The results indicated that the heat transfer coefficient and the friction factor should be properly selected in the design of the heat exchanger with corrugated channels.

Table 10. Design Value of Heat Exchangers

Heat Exchanger	Na-CO ₂ HX		HTR		LTR		Cooler	
Channel	Hot	Cold	Hot	Cold	Hot	Cold	Hot	Cold
Heat Transfer Capacity [MWt]	1528.7		1746.6		1070.3		873.7	
Total Heat Transfer Area [m ²]	42607.4		51615.2		82023.6		48900.4	
Single Channel Length [mm]	1046.6	1254.5	790.6	845.2	1235.7	1357.1	1271.7	1163.5
Total Number of Channel [ea]	7,917,247	6,605,593	16,929,875	15,836,829	17,213,028	15,673,301	7,478,706	8,174,331
Number of Channel on 1 Plate [ea]	179	149	256	239	263	239	218	239
PCHE Dimension Assuming 1 UNIT (L × W × H) [m]	1.05 × 0.60 × 176.3		0.79 × 0.60 × 264.3		1.23 × 0.60 × 261.7		0.97 × 0.60 × 113.5	
Characteristics of Corrugated Channel								
Bending Angle along Flow Direction [Deg]	180	113	170	137	170	130	100	114
Number of Turns along Flow Direction [ea]	0	125	79	86	123	135	127	116
Pitches across Flow Direction [mm]	3.3	4.0	2.3	2.5	2.3	2.5	2.7	2.5
Distance between Plate Edge & Channel [mm]	0	2.8	0.4	1.8	0.4	2.1	3.2	2.7

Table 11. Comparison between the Published Experimental Data and Simulation Data

Experimental data			Numerical data		Error (%)	
Cold channel pressure difference (Pa)			73220	65404.6	10.7	
Hot channel pressure difference (Pa)			24180	24609.5	1.8	
Cold channel Temperature difference (°C)			140.38	141.1	0.51	
Hot channel Temperature difference (°C)			169.6	165.46	2.4	
Reference conditions for comparison [21]						
Conditions	Cold channel mass flow	Hot channel mass flow	Cold channel temperature	Hot channel temperature	Cold channel pressure	Hot channel pressure
Case 2	(kg/s)	(kg/s)	(°C)	(°C)	(MPa)	(MPa)
(TIT 614)	0.0003152	0.0001445	107.9	279.9	8.28	2.52

between inlet and outlet.

In parallel with the PCHE type heat exchanger sizing, an airfoil shape fin heat exchanger has been newly designed. As a first step toward the development of the improved design concept of the PCHE, the CFD analysis was performed to assess the applicability of the CFD method. The FLUENT code was chosen as a CFD tool, and the calculated results were compared with available experimental data.

Table 11 shows a comparison between the numerical analysis and previous experimental data for the in-outlet pressure drop and the temperature difference of CO₂ in the hot and cold channels. The comparison conditions refer to the previous experimental data [21]. In Table 11 the error is calculated by Equation (2).

$$Error(\%) = \left| \frac{Experimental\ data - Numerical\ data}{Experimental\ data} \right| \times 100 \quad (1)$$

The results show that the numerical data for the in-outlet pressure drop of CO₂ in the hot channel and for the temperature difference of CO₂ in the hot and cold channels agree well with published experimental data, with a maximum error of 2.4 %. However, the simulated pressure drop of CO₂ in the cold channel is 10.7 % less than the value found in the experimental data. Nonetheless, considering the different conditions between the numerical analysis model and the real experiments, this 10.7 % error seems acceptable. These results validate the three-dimensional numerical analysis model of this study.

Fig. 14. Total Heat Transfer Rate and Pressure Drop in the Cold Channels of the Zigzag Channel PCHE and Airfoil Fin PCHEs

The new design concept was also evaluated by three-dimensional numerical analyses, which have showed that the airfoil shape fin heat exchangers conserve the total heat transfer rate and reduce the pressure drop to 1/14. The structural robustness of the PCHE has been evaluated by mechanical and stress analysis tools and its thermal and hydraulic performance is also under investigation by experimental tests.

4. TRANSIENT ANALYSIS

4.1 System Transient Analysis with the MMS-LMR

In order to simulate the system transient and evaluate control logics, the KALIMER-600 S-CO₂ Brayton cycle was modeled based on the MMS-LMR code. The basic modules in the MMS code have been developed for water and general gas plants like PWRs [24]. The property tables as well as the heat transfer models for sodium and supercritical CO₂ have been developed and implemented in the MMS code through user FORTRAN routines; this is called the MMS-LMR code.

Based on the MMS-LMR modules, we have developed the KALIMER-600 loop model for analyzing a sodium-cooled fast reactor, the KALIMER-600. The model is composed of a reactor module, various pipe modules, and an IHX, as well as Na-CO₂ HX, and HTR and LTR heat exchangers. The developed model is shown in Figure 15. For a simple analogy, we have modeled each loop (PHTS, IHTS, and Brayton cycle) as a single loop. The model is

composed of a core module, a loop module with various pipe modules including a pump module, an IHX, and various PCHE heat exchangers. Since a gas turbine for the S-CO₂ Brayton cycle has not yet been sufficiently developed, we assumed the turbine/generator as a heat sink in this model. The Na loop and the CO₂ cycle are modeled separately and, finally, linked to the PHTS/IHTS model. Additionally, the cooler in the S-CO₂ Brayton cycle was assumed to be an ideal cooler. This means the cooler's outlet condition is always the same (7.4MPa and 31.25 °C).

The core module was developed from a point kinetics equation for a nuclear core. The kinetic parameters are the prompt neutron generation time, the delayed neutron fraction, the poisoning effect from poisoning materials like Xeon and Iodine, and the reactivity coefficients from the sodium density change and the Doppler phenomena. In a fast reactor, the reactivity effect from the poisoning materials can be negligible due to the fast neutron spectrum. The coefficient for the sodium density is represented by the change of reactivity due to the change of sodium density in the core region.

We represented all the heat exchangers like the IHX, the Na-CO₂ HX, the HTR and the LTR HXs by using a pipehx module, a qmetal module, and another pipehx module in the MMS-LMR code. The pipehx module can simulate the heat transfer from a metal surface of a heat exchanger; the qmetal module can analyze the heat transfer in a metal. Each component and pipe data were retrieved from the heat balance of the KALIMER-600. Table 12 shows the analysis results for the steady state of the full

Fig. 15. MMS-LMR Model of KALIMER-600 with a Brayton Cycle

Table 12. Summary of the Steady State Calculation

Parameters	Reference	Result	Unit
Reactor power	100%	100.08	%
Temperature at core inlet/outlet	390/545	390.2/545.3	°C
PHTS flow rate	7731.3	7732.5	kg/sec
Temperature at IHX inlet/outlet in IHTS	364.0/526.0	364.1/526.1	°C
IHTS flow rate	7400.2	7401.9	kg/sec
Temperature at Na-CO ₂ HEX S-CO ₂ cycle	353.8/508	353.9/508	°C
Temperature at turbine outlet	394.2	394.8	°C
Temperature at HTR Hot side	394.2/203.1	394.8/204.9	°C
Cold side	185.8/353.9	192.6/353.8	°C
Temperature at LTR Hot side	203.1/91.20	204.9/85.6	°C
Cold side	84.8/184.2	68.2/167.8	°C
Pressure at HTR Hot side	7.6/7.53	7.59/7.46	MPa
Cold side	19.98/19.94	19.83/19.79	MPa
Pressure at LTR Hot side	7.53/7.46	7.46/7.4	MPa
Cold side	20.0/19.98	19.85/19.83	MPa
Flow rate in S-CO ₂ cycle	8076.6	8076.7	kg/sec
Compressor 1 side	5734.42	5707.0	kg/sec
Compressor 2 side	2342.21	2369.8	kg/sec

power operation of the KALIMER-600. There are some differences in temperatures for the cold side LTR; these could be overcome by further study of S-CO₂ compressors' data.

Then, the transient behavior was analyzed for the KALIMER-600 with S-CO₂ Brayton cycle. A simple power reduction and recovery event was chosen for the transient analysis. The analysis results were more or less

Fig. 16. Flow Rate and Temperature Change in the PHTS/IHTS and the Na-CO₂ Inlet/Outlet in the S-CO₂ Side for the Transient Operation

limited due to the lack of certain component data such as that for the turbines and the coolers. However, we concluded that the developed model had a good capability to simulate the KALIMER-600 plant. After appropriate turbines and coolers, including support mechanisms, are designed, we can finalize the MMS-LMR code and will develop the control strategies for the S-CO₂ Brayton cycle.

4.2 Assessment of Na-CO₂ Pressure Boundary Failure Accident

The potential tube rupture of an Na/CO₂ heat exchanger would generally involve the following technical issues. A high-pressure blowdown of CO₂ gas into the liquid sodium in a Na/CO₂ heat exchanger would cause a system pressurization coupled with a significant chemical reaction between the liquid sodium and the CO₂ gas, which could threaten the structural integrity of the heat exchanger itself and its related systems. Since these features would depend on the amount and the rate of the reaction heat release as well as on the type of reaction products, e.g. gaseous and non-gaseous, a boundary failure accident should be assessed to confirm the impact on plant safety and to check the effectiveness of the plant's protective methods. In previous works [25,26], it has been reported that the chemical interaction between CO₂ and liquid

sodium has fewer serious potential risks than those of an SWR. However, the consequences of this type of chemical interaction needs to be evaluated to achieve a more feasible and reliable system design.

Thus, a simple and reasonable numerical method to simulate the complex thermodynamic behaviors coupled with the chemical reaction between liquid sodium and CO₂ gas was developed, and the computer code STASCOR (System Transient Analyzer for Sodium and Carbon-diOxide Reaction) was formulated by implementing a detailed chemical reaction model and various system models. The long term behavior of an Na/CO₂ boundary failure event and its consequences, which lead to a system pressure transient, were evaluated for the shell-and-tube type Na/CO₂ heat exchanger of the KALIMER-600[27] employing a supercritical CO₂ Brayton cycle.

From the review of the event category of the SFR system [25], it was concluded that all the events except the Na-CO₂ reaction from the boundary failure are the same as those of the Rankine cycle because the secondary system of KALIMER-600 is non safety grade. The computer code "STASCOR" was developed; it has a simplified Mass & Energy Transfer Model, a CO₂ leak model, and a Dynamic System Models for Overpressure Protection System design.

In order to evaluate the consequences of the sodium-carbon dioxide chemical reaction in the Na-CO₂ heat exchanger of the KALIMER-600, the trends of the pressure and temperature variations during a boundary failure accident were investigated by using the STASCOR code, which was developed to qualitatively analyze thermodynamic behavior coupled with an Na-CO₂ chemical reaction. The analysis results for the long-term behavior of a tube rupture accident and its consequences, which lead to a significant system transient, are illustrated in this section. The capabilities of the simplified numerical quantification method implemented in the STASCOR code were evaluated as well. The physical model for a simplified mass and energy transfer (SMET) was developed by using the following assumptions;

- (i) the reaction occurs instantaneously if CO₂ gas leaks into the sodium phase,
- (ii) non-reacted quantity of CO₂ gas in the sodium phase is negligible,
- (iii) the generation quantity of the gaseous reaction product totally depends on the mass conversion ratio from the leaked CO₂ gas,
- (iv) exothermic energy from the chemical reaction is uniformly dissipated into the reaction zone (e.g. liquid sodium),
- (v) all of the mass of the gaseous reaction products flows into the cover gas space,
- (vi) the energy of the inflow gas is equalized with the sodium temperature heated by the chemical reaction
- (vii) the dissolution ratio of the gaseous reaction product into the liquid sodium is negligible.

Based on the physical model and assumptions, the energy balance between the cover gas and the shell-side sodium can be described as shown in Figure 17. The energy

balance presented here does not contain terms representing the phase change of the reaction products for a simplification of the phenomena.

Fig. 17. Energy Balance around the Cover Gas Region (SMET Model)

Fig. 18. Transient Behaviors of Reaction Source Terms

Fig. 19. System Pressure Transient during the Tube Rupture Event

By using the SMET model, the computer simulation code STASCOR was formulated based on the following simplifications or assumptions: flow is one-dimensional, shell-side sodium is incompressible, gas phase in the system is an ideal gas, system is totally adiabatic, and no mixing between liquid and gas phases exists.

The code has the capability to calculate the system pressure and temperature, the SDT (sodium drain tank) pressure and temperature, the sodium discharge behavior, the level change of the shell-side sodium, the termination time of the reaction, *etc.*

By using the code, the pressure and flow rate were calculated at a time after the event, as shown in Figure 18 and Figure 19. In this analysis, the CO₂ leak rate from the ruptured tubes was defined based on that of the sodium-water reaction of the conventional KALIMER-600 design. That is, it was assumed that a single double-ended guillotine break (DEGB) occurs at 0.1 sec (t_{SRI}) after a tube leak initiation and then the adjacent two more tubes are subsequently ruptured at 1 sec.

Figure 18 shows the yield rate of the gaseous reaction product, i.e. carbon monoxide (CO), corresponding to the CO₂ leak rate with the temperature dependent mass conversion ratio. As depicted in the figure, the production rate of the CO gas up to 1 sec, and increases rapidly in proportion to the extension of the design-basis CO₂ leak rate identified above; it was seen that the yielding rate of the CO gas increases slightly as the design-basis CO₂ leak rate is maintained. This is because the temperature of the reaction zone increases steadily due to the exothermic reaction heat generation ($\Delta_r H^\circ$). However, the quantity of these reaction source terms becomes very small as time

goes by, since the CO₂ leak rate decreases rapidly with the reactant isolation.

As depicted in Figure 19, the system pressure increases rapidly until the ruptured disk breaks, and it promptly decreases to a pressure level higher than the normal operation mode, which is maintained with small pressure rises or oscillations. This is mainly due to the characteristics of the pressure relief system, which is totally dependent on the interaction between the flow resistance of the sodium discharge pipe line and the static pressure effect of the remaining sodium inside the Na-CO₂ heat exchanger. The rupture disk break time is about 23.6 sec after leak initiation.

Based on the analysis results for the boundary failure accident in the Na-CO₂ heat exchanger, it can be preliminarily concluded that the STASCOR code has the capability to simulate a system transient regarding the various design conditions associated with a pressure relief system and that system's operational strategies; it can also be stated that the numerical quantification method implemented in this code is practicable for the purpose of system design.

Further applications to other types of heat exchangers, e.g. PCHE, are in progress to enhance heat exchanger capability; experimental verifications for the numerical models implemented in this code have been scheduled in order to enhance the code's reliability.

In view of reaction products, an Na-CO₂ reaction is different from the SWR phenomena since corrosive NaOH could not be generated from the chemical reaction. Thus, an inherent study of the CO₂ wastage has not been considered in our work. However, we are conducting some experimental studies to verify the Na-CO₂ chemical reaction model

Fig. 20. Flow Diagram of Na-CO₂ Reaction Test

since we should evaluate the possibility of wastage due to the high pressure and temperature leakage. Figure 20 shows the schematics of the Na-CO₂ chemical reaction test apparatus; the apparatus is composed of two-types of test-section. One of test-sections is installed to investigate a surface-reaction fundamental characteristic between Na and CO₂. The other is mounted to see more real situations, such as the injection of the CO₂ gas into the sodium.

5. CONCLUSIONS

Systematic research has been conducted to develop a supercritical carbon dioxide Brayton cycle energy conversion system coupled with the KALIMER-600 sodium-cooled fast reactor. Through the studies, a supercritical CO₂ Brayton cycle system coupled to the KALIMER-600 was developed with the design and evaluation of major components such as S-CO₂ compressors, S-CO₂ turbine, and S-CO₂ heat exchangers necessary to the system. In the course of system development, several computer codes were developed for system and component design. The technology and computer code produced through the

system development could be used to develop other power plants, such as fossil fuel plants, SFRs, VHTRs, and fusion reactors.

In the case of the KALIMER-600 operating conditions, the cycle efficiency and the plant net efficiency are obtained at 42.8% and 40.3%, respectively. From the CFD analysis of the S-CO₂ turbomachinery, it seems that the one-dimensional analysis codes should be enhanced to supply the design parameters to the CFD tool by considering the loss model and more empirical manufacturing experiences. For the better performance of the S-CO₂ turbomachinery, a semi-three dimensional design tool should be developed before the three dimensional CFD analysis. The new airfoil shape PCHE was developed by using the CFD analysis, which, while maintaining the heat transfer characteristics, offers 1/14 of the pressure loss compared with the previous zigzag type PCHE.

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REFERENCES

- [1] V. Dostal, M.J. Driscoll, P. Hejzlar, N.E. Todreas, "A Supercritical CO₂ Gas Turbine Power Cycle for Next-Generation Nuclear Reactors," Proceedings of ICONE-10, Arlington, 2002
- [2] V. Dostal, P. Hejzlar, M. J. Driscoll, and N. E. Todreas, "A Supercritical CO₂ Brayton Cycle for Advanced Reactor Applications," Trans. Am. Nucl. Soc., 85, 2001
- [3] N. Kishohara, S. Kotake, and T. Sakamoto, Studies of Supercritical CO₂ Gas Turbine Power Generation Fast Reactor, JAEA Report, JAEA-Review 2009-040
- [4] HEATRIC website, <http://www.heatric.com>
- [5] A.V. Moiseyev, J. J. Sienicki, and D. C. Wade, "Turbine Design for a Supercritical Carbon Dioxide Gas Turbine Brayton Cycle," ICAPP-2003, 3064, Cordoba, Spain, May 4-7, 2003
- [6] P. E. MacDonald, J. Bongiorno, Design of an Actinide Burning, Lead or Lead-Bismuth Cooled Reactor That Produces Low Cost Electricity, Annual report, INEEL/EXT-01-01376, 2001
- [7] E.W. Lemmon, M.O. McLinden, and M.L. Huber, NIST Reference Fluid Thermodynamic and Transport Properties-REFPROP, Version 7.0, User's Guide, National Institute of Standards and Technology, 2002
- [8] A. Moiseyev, Passive Flow Analysis of the STAR-LM and STAR-H2 Systems, Dissertation of Texas A&M University, 2003
- [9] D.H. Han, et.al., KALIMER-600 Conceptual Design Report, KAERI/TR-3381/2007, KAERI Technical Report, 2007
- [10] R. Fuller, "Turbo-Machinery Considerations Using Supercritical Carbon Dioxide Working Fluid for a Closed Brayton Cycle," presented at the MIT CANES Symposium on Supercritical CO₂ Power Cycle, 2007
- [11] H.W. Oh, Investigation on the Design and Performance Analysis of Centrifugal Turbomachinery, Ph. D Dissertation, KAIST, 1998
- [12] S.O. Kim, J. J. Sienicki, Supercritical Carbon Dioxide Brayton Cycle Energy Conversion, I-NERI Final Report, 2005-001-K, 2009
- [13] D.G. Wilson, The Design of High-Efficiency Turbomachinery and Gas Turbines, The MIT Press, 1985
- [14] M.P. Boyce, Gas Turbine Engineering Handbook, Second Edition, Gulf Professional Publishing, 2002
- [15] A.V. Moiseyev, J. J. Sienicki, and D. C. Wade, "Cycle Analysis of Supercritical CO₂ Gas Turbine Brayton Cycle Power Conversion System for Liquid Metal-Cooled Fast Reactors," Proc. 11th Int. Conf. on Nuclear Engineering, Tokyo, Japan, April 20-23, 2003
- [16] T.W. Kim, N.H. Kim, K.Y. Suh, and S.O. Kim, "Computational Analysis of Supercritical Carbon Dioxide Flow around A Turbine and Compressor Blade," Proc. of ICONE15, April 22-26, 2007, Nagoya, Japan
- [17] S. J. Dewson, C. Grady, Hetric Workshop at MIT, Cambridge, Ma, U.S.A., October 2nd., 2003
- [18] H. Ishikawa, S. Miyahara and Y. Yoshizawa, "Experimental Study of Sodium-Carbon Dioxide Reaction," Proc. of ICAPP-2005, Seoul, Korea, May 15-19, 2005
- [19] K. Gezelius, M.J. Driscoll, P. Hejzlar, Design of Compact Intermediate Heat Exchangers for Gas Cooled Fast Reactor, MIT-ANP-TR-103, 2004
- [20] N. Tsuzuki, Y. Kato, and T. Ishizuka, "High Performance Printed Circuit Heat Exchanger, Applied Thermal Engineering," Vol. 27, pp. 1702~1707, 2007
- [21] T. Ishizuka, Y. Kato, et.al., "Thermal-Hydraulic Characteristics of a Printed Circuit Heat Exchanger in a Supercritical CO₂ Loop", NURETH-11, Avignon, France, pp. 218~232, 2005
- [22] H. Song et al., "Experimental Investigations of a Printed circuit heat exchanger for Supercritical CO₂ and Water Heat Exchange", Proceedings of 5th Korea-Japan Symposium Thermal Hydraulics and Safety, Jeju, Korea, 2006
- [23] S.C. Song, "Thermal-Hydraulic Performance of a Printed Circuit Heat Exchanger in an Air Test Loop", MS Thesis, Korea Advanced Institute of Science and Technology, 2006
- [24] nHance Technology, Inc., MMS Basic Manual
- [25] C. Latge, G. Rodriguez and N. Simon, "Supercritical CO₂ Brayton Cycle for SFR : Na-CO₂ Interaction and Consequences on Design and Operation," GLOBAL-2005, Tsukuba, Japan, Oct. 9-13, 2005
- [26] H. Ishikawa, S. Miyahara and Y. Yoshizawa, "Experimental Study of Sodium-Carbon Dioxide Reaction," Proc. of ICAPP05, Seoul, Korea, May 15-19, 2005
- [27] D.H. Hahn, et al., "Design Features of Advanced Sodium-Cooled Fast Reactor KALIMER-600," Proc. of ICAPP04, Pittsburgh, PA USA, June 13-17, 2004