Integrated and visual performance evaluation model for thermal systems and its application to an HTGR cogeneration system

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Abstract: An integrated and visual model EXCEM-MFM (EXergy, Cost, Energy and Mass - Multilevel Flow Model) has been proposed in this study to comprehensively analyze and evaluate the performances of thermal systems by coupling two models: EXCEM model and MFM. In the EXCEM-MFM model, MFM is used to provide analysis frameworks for exergy, cost, energy and mass four parameters, and EXCEM is used to calculate the flow values of these four parameters for MFM based on the provided framework. In this study, we used the tools and technologies of computer science and software engineering to materialize the model. Moreover, the feasibility and application potential of this proposed EXCEM-MFM model has been demonstrated by the example application of a comprehensive performance study of a typical High Temperature Gas Rector (HTGR) cogeneration system by taking into account the thermodynamic and economic perspectives.

Keywords: performance evaluation method; EXCEM; MFM; HTGR

1 Introduction

In recent years, increasing attention has been paid to environmental sustainability through efficient use of resources whilst attempting to minimize environmental pollutions. Conversely, economic aspects are also crucial for energy technologies to survive in the present competitive market. In the context of thermal systems, the options need to be analyzed and evaluated comprehensively from thermodynamic, economic and environmental perspectives to improve the sustainability of energy systems [1].

The EXCEM (EXergy, Cost, Energy and Mass) model[2] has been proposed to be applied for conducting the energy, exergy and exergy-based costing analyses for optimizing performances of various thermal systems based on the first and second laws of thermodynamic as well as exergy-based costing method. The basic philosophies are that in order to investigate thermodynamic performance of a thermal system, both energy and exergy analyses are necessary to measure energy losses in quantity and

quality, whereas exergy-based costing method can determine the cost of each product unit in a cogeneration system, which was demonstrated in previous studies [3-5].

However, the EXCEM model has not been broadly used due to the difficulties in understanding and application. Unlike exergy, energy and mass flows are all based on scientific laws, while exergy-based cost allocation is a subjective issue that is different according to the aim and type of the target system, as well as other considerations. Therefore, an effective and flexible organizational method is necessary for these four parameters. In this context, an integrated and visual model – EXCEM-MFM (Exergy, Cost, Energy and Mass - Multilevel Flow Model) − is proposed in the present study to conduct an integrated analysis and assessment for thermal systems in a feasible and easily understandable way by coupling EXCEM and MFM. MFM is a kind of effective modeling method to represent the ''internal process'' of physical behavior by network structure of flows of mass, energy and information, by using a set of well-defined symbols as demonstrated in past studies[6–8]. Therefore, it is easy to extend MFM to be

combined with EXCEM to represent the flows of mass, energy, exergy and cost without the needs for a large amount of basic definitions, explanations, debugging and discussion. When four-parameters mass, energy, exergy and cost are organized and the framework is constructed based on MFM, various analyses can be conducted. The analyses can be carried out by using the conservation laws of mass and energy, the second law of thermodynamic and exergy-based costing method of EXCEM model based on the constructed framework. The analysis results are flow values of the four parameters, which will be returned to MFM. Subsequently, values of the integrated assessment indicators can be obtained by grouping the MFM flow values. In order to conduct abundant thermodynamic and cost calculations efficiently, a software platform − EXCEM-MFM Studio − has been developed to materialize the EXCEM-MFM model.

This research demonstrates the example of a typical High Temperature Gas Reactor (HTGR) cogeneration system with two products (hydrogen by thermochemical method and electricity by gas turbine)[9-12] that was analyzed based on the proposed EXCEM-MFM model. The feasibility and future possibilities for application of the proposed model were demonstrated by the obtained findings.

This paper comprised of four sections, in which the following section addresses the basic philosophy of the EXCEM-MFM model is given in the next section; followed by the third section that elaborates the application of the proposed model for an HTGR cogeneration system. The analysis results are reported in section four, followed by the conclusions in the final section.

2 Proposal of EXCEM-MFM Model

2.1 Exergy, Cost, Energy, and Mass (EXCEM) model

2.1.1 The concept of EXCEM Model

Four key parameters, exergy, cost, energy and mass, are used to investigate the performance of thermal systems from thermodynamic and economic perspectives. This model is abbreviated and termed as EXCEM model, which is presented in Fig.1 [2]. The

fundamental balance equation for EXCEM model is shown in Eq.(1), in which *Input* and *Output* respectively refer to quantities entering and exiting through system boundaries. *Generation* and *Consumption* respectively refer to produced and consumed quantities within the system. *Accumulation* refers to change (either positive or negative) of the quantity within the system. General balance equations related to applying the exergy, cost, energy and mass are represented by the following Eqs. (2) to (5).
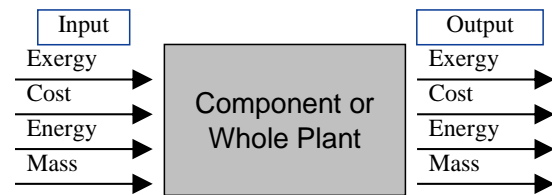

Fig.1 EXCEM model for a component or whole plant.

$$Input + Generation\ Consumption\ Accumulation = Output \tag{1}$$

$$Ex_{Input} - Ex_{Consumption} - Ex_{Accumulation} = Ex_{Output} \tag{2}$$

$$C_{Input} + C_{Generation} - C_{Accumulation} = C_{Output} \tag{3}$$

$$E_{Input} - E_{Accumulation} = E_{Output} \tag{4}$$

$$M_{Input} - M_{Accumulation} = M_{Output} \tag{5}$$

In the EXCEM model, both energy and mass are subject to conservation laws. Exergy is consumed ($Ex_{Consumption}$) due to exergy destructions. Cost is generated from the capital costs and relevant operation and maintenance (OM) costs. C_{input} and C_{output} represent the cost of the input materials and output materials respectively, whereas $C_{Generation}$ is the sum of capital cost and relevant manipulation operation (MO) cost. Generally, the accumulated items can be considered as loss attributable to the material stream vented to the environment. Therefore, exergy accumulation is always considered as an exergy loss because of the material stream vented to the surroundings. Exergy destruction is the exergy destroyed by irreversibility within the control volume attributable to one or more of the three principal irreversibilities associated with chemical reaction, heat transfer, and mechanical friction.

Based on the EXCEM model, exergy and exergy-based costing analyses can be conducted for detailed thermal systems, as depicted in Fig. 2. Based

on the flow values in mass flow, unknown thermodynamic parameters, such as temperatures and pressures in various locations, are calculable based on the energy conservation law. Furthermore, based on the values of mass flows and thermodynamic parameters, the values in exergy flows are obtainable using the second law of thermodynamics. Finally, the exergy analysis can be conducted based on exergy flows, and the exergy-based costing analysis can be conducted based on the combination of exergy flows and the cost information of the equipment in the target system [3-5].
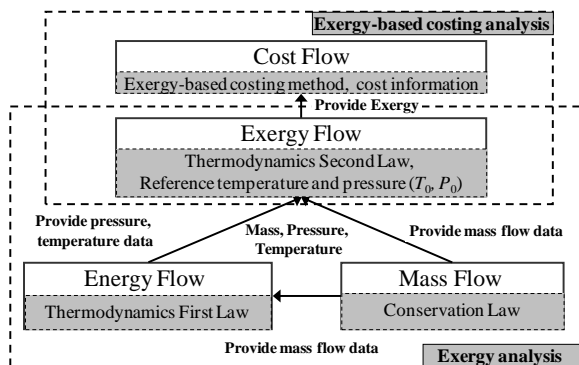

Fig.2 Exergy and exergy-based costing analyses based on EXCEM model.

2.1.2 Exergy analysis based on EXCEM model

Exergy analysis is designed to quantitatively measure the thermodynamic performance using exergy efficiency. The exergy efficiency is obtained by calculating the ratio of exergy value of the product-Ex_P to the exergy value of the fuel-Ex_F, as given by Eq.(6) for one component or the whole system. Furthermore, Ex_D and Ex_L respectively represent the corresponding exergy destruction and exergy loss. For example, exergy fuel $-Ex_F-$ for a compressor is the driver of electricity power; the exergy product$- Ex_{P-}$ is the increased exergy of the compressed working fluid.

$$\varepsilon = \frac{Ex_P}{Ex_F} = 1 - \frac{(Ex_D + Ex_L)}{Ex_F} \qquad (6)$$

2.1.3 Exergy-based costing analysis

Exergy-based costing analysis combines exergy analysis and economic analysis based on the concept that exergy is the rational basis for assigning costs. It aims to calculate the cost of each product generated in a cogeneration system. The reasoning behind the exergy-based costing method is that cost should

represent value. For this reason, the equal working ability (exergy) of energy carriers can be considered as having equal values. As shown in Eqs.(7) and (8), the parameter Z represents the sum of capital cost and the Management and Operation (MO) cost per second, because the C_F and C_P respectively are the cost of exergy fuel flow $-Ex_F-$ and exergy product $- Ex_P -$ the speed of which are expressed in the unit of second. The cost of exergy product is obtained by adding the cost of exergy fuel to the costs of the corresponding components; because both of them exist for obtaining the exergy product. In addition, c_F and c_P represent unit cost of exergy fuel and exergy product respectively, through which the cost allocation for multiple products can be realized flexibly.

$$c_F = \frac{C_F}{Ex_F} \qquad (7)$$

$$c_P = \frac{C_P}{Ex_P} = \frac{C_F + Z}{Ex_P} \qquad (8)$$

2.2 MFM (Multilevel Flow Model)

MFM is a type of functional modeling method, which is not only to describe the semantics of any object on the hierarchical structure of goals, functions and components, but also to represent the "internal process" of physical behavior by network structure of flows of mass, energy and information. Within this structure, special graphs are drawn for MFM model of the target object by using a set of standard symbols as shown in Fig.3 and Table1[6]. Traditionally, MFM has been mainly used in the process control areas for deducing various human-machine system technologies ranging from signal validation, fault monitoring and fault diagnosis to procedure generation and human modeling [7, 8]. In this study, the application of MFM is extended to represent the semantic structure of the EXCEM model.
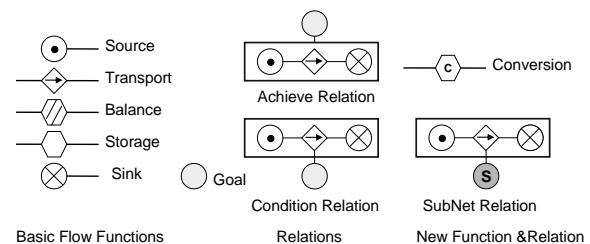

Fig. 3 MFM functions and relations.

Table 1. Basic MFM connection and computation rules.

Type	Connection (Input/Output)	Computation rules
Source	Transport(0/1)	$F_{in}=0, F_s=0$
Sink	Transport(1/0)	$F_{out}=0, F_s=0$
Transport	Source, Balance, Storage and Sink(1/1)	$F_{in}=F_{out}, F_s=0$
Storage	Transport(1/1)	$\Delta F_s=F_{in}-F_{out}$
Balance	Transport (Multi/Multi)	$\Sigma F_{in}=\Sigma F_{out}, F_s=0$
Conversion	Transport (Multi/Multi)	$\Sigma F_{in}=\Sigma F_{out}, F_s=0$

F_{in}: input flow; F_{out}: output flow; F_s: Storage

2.3 EXCEM-MFM Model

A new integrated analysis model for thermal systems, the multiple flow model of exergy, cost, energy and mass (EXCEM-MFM) is proposed in this study by coupling EXCEM and MFM as shown in Fig.4, and the flowchart for conducting this method as depicted in Fig.5. First, MFM framework of exergy, cost, energy and mass are constructed for the target thermal system, if the constructed MFM can pass the assessment according to the connection rules as shown in Table 1. Calculation processes among the four kinds of flows will commence, otherwise the constructed MFM needs to be revised until it can satisfy all the rules. In calculation processes, first, various physical parameters and mass flow values are calculated by using basic conservation laws of energy and mass based on initial known parameters, hence energy flow values can be obtained. Exergy flow values are obtained in the next step by using physical parameters and mass flow values based on defined reference environment conditions. Finally, cost flow values are obtained by using exergy-based allocation method according to the obtained exergy flow and cost information concerning the components. If all flow values of EXCEM-MFM are obtained, various performance parameters such as energy efficiency and exergy efficiency, cost per unit product and CO_2 emission per unit product can be obtained by grouping the flow values in MFM.
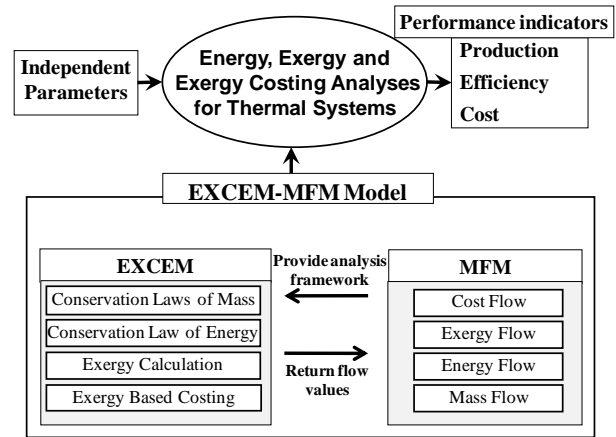

Fig.4 Proposed EXCEM-MFM method.

The representations and physical meanings of mass flow and energy flow using MFM had been defined and explained very well in past studies [6,7,8]. However, since it is the first time to apply MFM to represent exergy and cost, the basic definitions are necessary. Since exergy is defined as the maximal work attainable from an energy carrier under the given environment condition, it is considered as the quality (working potential) of energy. Thus, similarly but unlike energy flow; exergy flow can also be depicted by using MFM. The most important difference between energy and exergy flows is that in exergy flows, there are "sink" processes due to exergy destructions in heat exchanges, mechanical frictions, chemical reactions, *etc.*, which do not exist in energy flows. Furthermore, based on exergy, costs are allocated to form a cost flow. In cost flows, sources are costs concerning the components including capital cost and MO costs, whereas sinks represent the desired final products of the system. There are exergy-based cost allocation processes between sources and sinks. As mentioned above, unlike the flows of exergy, energy and mass constructed based on scientific laws, costs are allocated subjectively depending on the type and purpose of a system and other economic considerations. In other word, desired products and exergy-based costing processes in cost MFM can be different for the same thermal system according to the users' design.
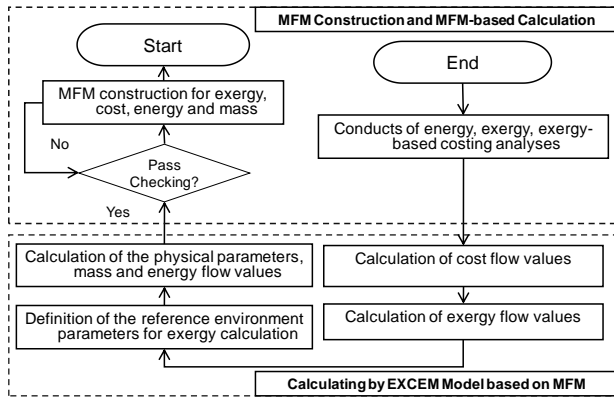
Fig.5 Flowchart for conducting analyses
using EXCEM-MFM method.

3 Application of EXCEM-MFM model to an HTGR cogeneration system

A typical HTGR cogeneration system that produces hydrogen and electricity simultaneously is chosen as the target system in this study and presented in Fig.6. Both Gas Turbine High Temperature Reactor 300 (GTHTR300) and Gas Turbine High Temperature Reactor 300 Cogeneration (GTHTR300C) of the High Temperature Test Rector (HTTR) project studied by Japan Atomic Energy Agency (JAEA) are very advanced HTGR options, which are still in the design stage. They have been studied from the viewpoints of the whole system design concept and safety [9,10]. The economic investigation of GTHTR300 with electricity as the only outcome has also been conducted by estimating all the relevant cost information associated with the equipment, nuclear fuel, management and operation [11]. With regards to HTGR cogeneration systems such as the GTHTR300C that simultaneously generate hydrogen and electricity, there are several possible development scenarios with different operating conditions that satisfy different demands, which have been proposed by JAEA and the Japan Atomic Industrial Forum (JAIF) [12]. However, the systems can not attract enough business investments until their feasibility and profitability are quantitatively demonstrated. In particular, the specific costs per unit of hydrogen and electricity have never been reported for the GTHTR300C because of the absence of a broadly-acceptable and feasible method for allocating system costs to multiple products. Therefore, the performance of the HTGR cogeneration system as presented in Fig.6 will be investigated from

thermodynamic and economic perspectives by using the proposed EXCEM-MFM model.

The target HTGR is presented in Fig. 6, with the initial design parameters were kept constant. The heat capacity of the rector is 600 MWt; the inlet and outlet temperatures of the reactor are at 594 and 950° C respectively. The inlet and outlet temperatures of the second loop of the IS process for producing hydrogen are at 900 and 500° C respectively according to the reaction conditions. The helium and water flows in the main loop and the second loops are numbered to identify their locations. In the main loop, for numbers 1– 7, helium from the reactor is first used to provide high-temperature heat for the Iodine-Sulfur (IS) hydrogen generation process through the Intermediate heat exchanger (IHX). Subsequently, helium from the IHX enters the gas turbine directly to generate electric power by turning the generator. Finally, the helium flow from the gas turbine first passes through the recuperator. It is then cooled by cold water in a precooler for ease of compression; and it returns to the reactor through the compressor and recuperator.
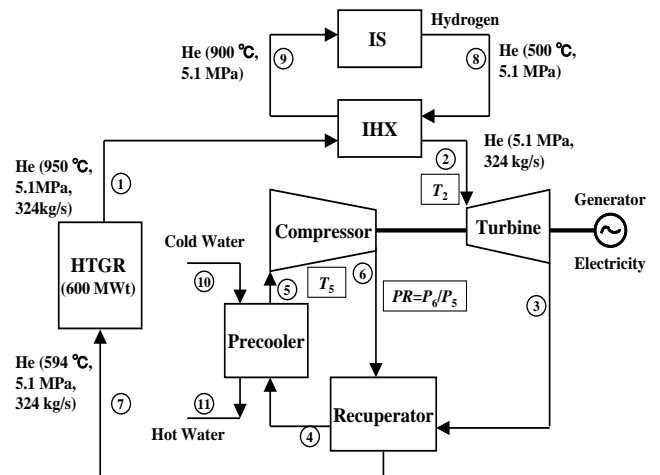

Fig.6 Flow sheet of the target HTGR cogeneration system.

Basic thermodynamic analysis based on mass and energy conservation laws is the basis of exergy analysis and exergy-based costing analysis. The main process of physical parameters are related according to the first law of thermodynamics and mass conservation law based on the MFM as shown in Fig.7. Consequently, all temperatures, mass flows, heat flows, and system efficiencies are obtainable. The unknown physical parameters of the processes

are obtainable using a stable thermodynamic model relating the process parameters. The obtained physical parameters will be used to conduct exergy analysis in the next step.
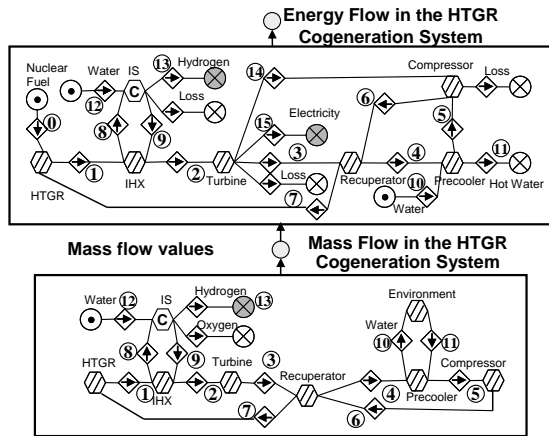

Fig.7 MFM for the basic energy analysis.

The basic thermodynamic analysis equations are listed in Table 2. Because all leakages are neglected, the helium mass in the main loop (from M1 to M7) are constant, whereas M8 and M10 equals M9 and M11 respectively. In the present study, heat exchangers (recuperator, precooler, reactor, IHX) are simplified as totally adiabatic, thus no heat loss occurs during heat exchange processes. Therefore, the input energy equals the output energy for the reactor, IHX, recuperator and precooler. However, there are energy losses in turbine, compressor, IS process and other processes within the whole system. These are due to mechanical frictions and chemical reactions. The ratios of their output and input energy are considered as energy efficiency.

Table 2 Thermodynamic analysis for the HTGR cogeneration system

Component	Input	Output
Reactor	E0	E1-E7
IHX	E1-E2	E8-E9
Turbine	E2-E3	E15
Recuperator	E3-E4	E7-E6
Compressor	E14	E6-E5
IS	E8-E9	E13
Precooler	E4-E5	E10-E11
Whole System	E0	E13+E15

IS: IS hydrogen generation process

Correspondingly, the exergy MFM of the HTGR cogeneration system is constructed as shown in Fig.8, and the exergy analysis processes of components and the whole system based on MFM are shown in Table 3. The output is always less than the input in exergy

analysis due to various exergy destructions, although energy remains balanced in the same process.
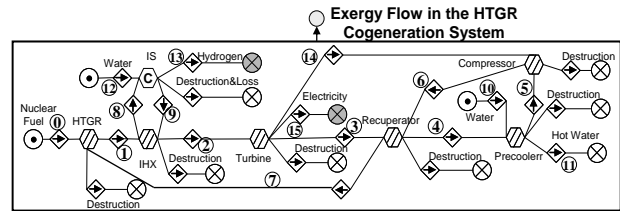

Fig.8 MFM for the exergy analysis.

Table 3 Exergy analysis for the HTGR cogeneration system.

Component	Ex$_F$	Ex$_P$
HTGR	Ex0	Ex1-Ex7
IHX	Ex1-Ex2	Ex8-Ex9
Turbine	Ex2-Ex3	Ex14+Ex15
Recuperator	Ex3-Ex4	Ex7-Ex6
Compressor &Precooler	Ex14	Ex6-Ex4
IS	Ex12+(Ex8-Ex9)	Ex13
Whole System	Ex0+Ex12	Ex13+Ex15

IS: IS hydrogen generation process

When all types of necessary cost information associated with the equipment and fuel are obtained, the production cost per unit of product is obtainable using the exergy-based costing method. Unlike the basic thermodynamic and exergy analyses, which are conducted based on scientific laws, the cost allocation method is a subjective issue that might be different according to the definitions of the aim and type of the system, as well as individual considerations. For this study, the exergy-based costing analysis is conducted as presented in Fig. 9. The reasoning behind this approach is that IHX and IS equipment were considered to exist for hydrogen production, whereas the compressor, turbine, precooler, and recuperator equipment were considered to exist for electricity production. Consequently, costs associated with the reactor are divided according to the exergy consumptions, respectively, for hydrogen and electricity productions. The respective calculation methods are presented in Eqs. (9) and (10): $Ex_{Reactor, P}$ is the exergy product provided by the reactor; $Ex_{IHX, F}$ is the exergy fuel for IHX; and Z is the cost associated with each device.
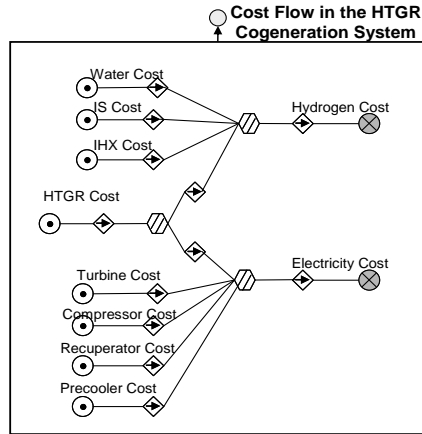
Fig.9 MFM for the exergy based costing analysis.

$$Cost_{\text{Hydrogen}} = \frac{\left(Z_{\text{IHX}} + Z_{\text{IS}} + \dfrac{Z_{\text{Reactor}}(Ex_{\text{IHX,F}})}{Ex_{\text{Reactor,P}}}\right)}{Production_{\text{Hydrogen}}} \quad (9)$$

$$Cost_{\text{Electricity}} = \frac{\left(Z_{\text{Recuperator}} + Z_{\text{Precooler}} + Z_{\text{Compressor}} + Z_{\text{Turbine}} + Z_{\text{Reactor}}\left(1 - \dfrac{Ex_{\text{IHX,F}}}{Ex_{\text{Reactor,P}}}\right)\right)}{Production_{\text{Electricity}}} \quad (10)$$

Calculating various operating conditions is difficult due to the many equations, relations, and constraints used for the analysis models. Therefore, a software platform "EXCEM-MFM Studio" was developed. It supports energy, exergy and exergy-based costing analyses based on EXCEM model and MFM. EXCEM-MFM Studio considers thermodynamic, exergy, and exergy-based costing analyses as operational modules; whereas mass flow data, known physical parameters, and cost information are used as initial data.

4 Analysis results

Based on analysis models described above together with the relevant thermodynamic and cost data, as well as the initial operating condition provided by JAEA, the obtained exergy analysis result is shown in Table 4. The results show that the target HTGR co-generation system is thermodynamic-efficient. Furthermore, three optimized cases are proposed based on exergy, exergy-based costing analysis results at various operating conditions, which have been demonstrated to be economically competitive compared with other hydrogen and electricity generation systems as shown in Fig.10 (SMR: Steam Methane Reforming, PWR: Pressurized Water Reactor). Thus, the feasibility of the proposed EXCEM-MFM method has also been proven.

Table 4 Exergy analysis result of the equipment in the selected HTGR cogeneration system

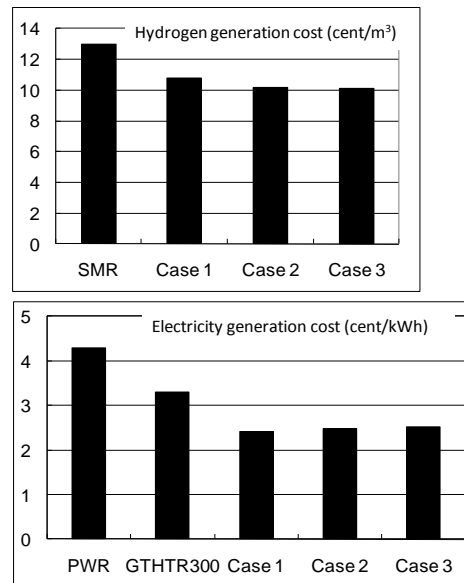| Component	ExF(MWt)	ExP(MWt)	(%)
Reactor	600	427.22	71.2
IHX	125.70	116.17	92.43
IS	116.17	69.54	59.86
Turbine	428.34	412.58	96.32
Recuperator	361.52	356.34	98.57
Comperssor &Precooler	211.28	132.00	62.47
Whole System	600	270.84	45.14

IS: IS hydrogen generation process

Fig.10 Economic performance comparison of the proposed three deployment scenarios of HTGR and other hydrogen and electricity generation systems.

The above analysis results have validated the proposed EXCEM-MFM as an effective and flexible integrated analysis model. In the future, more comparison studies will be conducted using the model to emphasize on its feasibility. For example, the differences in MFM construction and obtained result between the exergy-based costing method and the energy-based costing method will be studied.

5 Conclusions and perspectives

In this study, an integrated and visual model – that is, EXCEM-MFM − was proposed based on EXCEM and MFM models to comprehensively analyze and evaluate performances of thermal systems from thermodynamic and economic perspectives. A computer software platform has been developed dedicated to conduct various analyses based on EXCEM-MFM model. The feasibility and potential application of the proposed EXCEM-MFM model

were practically demonstrated through its successful application to a typical HTGR cogeneration system. In future work, the model is expected to be applied for conducting more analyses, including more cogeneration systems, more cost allocation method comparisons and sensitive analysis.

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