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Analysis and Optimization of a HTGR Cogeneration System's Performance Based on Integrated Analysis and Evaluation Methodology of Energy Systems for Sustainable Development (IAEMSD)

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ABSTRACT

An integrated and visual method has been proposed for analyzing and evaluating performances of thermal systems comprehensively by coupling EXCEM (Exergy, Cost, Energy and Mass) model and MFM (Multilevel Flow Model). Tools and technologies of computer science and software engineering have been use to materialize the method. The feasibility and promising application possibility of this proposed method has been demonstrated by the findings of studying performances of a typical High Temperature Gas Rector (HTGR) cogeneration system from thermodynamic and economic aspects comprehensively as an example.

KEYWORDS

IAEMSD , EXCEM model, Multilevel Flow Model ,HTGR, Cogeneration system, Performance analysis, Exergy analysis, Exergy-based cost analysis

INTRODUCTION

Attaining sustainable development is assisted if resources are used efficiently for lengthening the lives of finite resources and decreasing environmental pollutions that otherwise might occur. Furthermore, economic performance is crucial for an energy technology to survive in the keen market competition. Therefore, thermal system opinions need to be analyzed and evaluated comprehensively from thermodynamic, economic and environmental aspects for improving the sustainable development of energy systems [1]. Thus, the EXCEM (Exergy, Cost, Energy and Mass) model [2] has been proposed to conduct the energy, exergy and exergy based costing (thermoeconomic, Exergoeconomic analyses) analyses for analyzing and optimizing performances of various thermal systems based on the thermodynamic first/second laws and exergy based costing method. Because, in order to investigate thermodynamic performance of a thermal system, both energy analysis and exergy analysis are necessary to measure energy losses in quantity and quality based on the thermodynamic first and second law; and, exergy based costing method can determine the cost of unit product in a cogeneration system, which has been demonstrated in many past studies [3, 4, 5].

But the EXCEM model has not been used broadly due to the difficulties in understanding and application, especially different with exergy, energy and mass flows which are all based on the scientific laws, the exergy based cost allocation is a subjective issue which is different according to the aim and type of the target system and other considerations. Thus an effective and flexible organization method is necessary to deal with these four parameters. Comparing with the intricate integration analysis concept in past studies, a visual method- EXCEM-MFM (Exergy, Cost, Energy and Mass Multilevel Flow Model) is proposed in this study to conduct an integrated analysis and assessment for thermal systems based on the combination of EXCEM and MFM. In this model, MFM is used to construct and organize mass, energy, exergy and cost flows as a framework, then various analyses are conducted using the conservation laws of mass and energy, thermodynamic second law and exergy based costing method of EXCEM model based on the MFM's representation and organization. After that, the calculated out flow values are returned to MFM as flow values of processes in MFM. At last, values of the integrated assessment indicators are obtained by grouping MFM flow values. And a software platform-EXCEM-MFM Studio has been developed to materialize the EXCEM-MFM model in order to deal with abundant thermodynamic and cost equations efficiently in this study.

As an example, a typical High Temperature Gas Reactor (HTGR) cogeneration system with two products (hydrogen by thermochemical method and electricity by gas turbine) is analyzed based on the proposed EXCEM-MFM model. And the feasibility and the future promising application of the proposed method have been demonstrated by obtained findings of conducting the example.

PROPOSAL OF EXCEM-MFM MODEL

1. EXCEM (Exergy, Cost, Energy and Mass) Model

Traditionally, exergy analysis is conducted together with the conservation principles of mass and energy to obtain the necessary physical parameters. Exergy based costing analysis is carried out based on the exergy flow and various cost information associated with the equipments in the target system. Therefore, the four key parameters- exergy, cost, energy and mass are used to investigate the performance of thermal systems from thermodynamic and economic aspects together which is called EXCEM model as shown in Fig.1. The fundamental balance equation for EXCEM model is shown in Eq.(1), where "Input" and "Output" refer to quantities entering and exiting through system boundaries, respectively. "Generation" and "Consumption" refer, respectively, to quantities produced and consumed within the system. Accumulation refers to change (either positive or negative) of the quantity within the system. The general balance equations applying to the exergy, cost, energy and mass are represented by the following Eqs. (2) to (5).

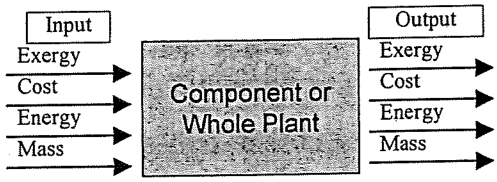

Fig.1 EXCEM model for components or whole plant.

Input + Generation -Consumption – Accumulation= Output	(1)
$Ex_{In} - Ex_{Consumption} - Ex_{Accumulation} = Ex_{Out}$	(2)
$C_{In} + C_{Generation} - G_{Accumulation} = C_{out}$	(3)
$E_{In} - E_{Accumulation} = E_{Out}$	(4)
$M_{In} - M_{Accumulation} = M_{Out}$	(5)

In the EXCEM model, both energy and mass are subject to conservation laws. While exergy is consumed ($Ex_{Consumption}$) due to exergy destructions, and cost is generated due to capital cost and relevant manipulation and operation (MO) cost ($C_{Generation}$). Generally speaking, the accumulation item can be considered as loss due to the material stream vented to the surroundings. Therefore, exergy accumulation always is considered as exergy loss due to material streams vented to the surroundings. While exergy destruction is exergy destroyed by irreversibility within the control volume due to one or more of three principal irreversibilities associated with chemical reactions, heat transfers and mechanical frictions respectively.

1.1 Exergy Analysis Based on EXCEM Model

Exergy analysis aims to measure thermodynamic performance of a system quantitatively by calculating its exergy efficiency. 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 a component or whole system. And, Ex_D and Ex_L indicate the corresponding exergy destruction and exergy loss respectively. For example, for a compressor, the exergy fuel-Ex_F is the driver power electricity and the exergy product-Ex_P is the increased exergy of the compressed working fluid.

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

1.2. Exergy based Costing Analysis Based on EXCEM Model

Exergy based costing analysis combines exergy analysis and economic analysis based on the concept that exergy is the rational basis for assigning costs aiming 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, and same working ability (exergy) of energy carriers can be considered as with same values. And, as shown in Eqs.(7) and (8), the "Z" represents the sum of capital cost and the Management and Operation (MO) cost per unit second of the component, the "C_F" represents the cost of exergy fuel-Ex_F which is described in the preceding paragraph of exergy analysis, and the "C_P" represents the cost of exergy product-the "Ex_P" also described in the preceding paragraph of exergy analysis. The cost of exergy product is obtained by add the cost of exergy fuel to the costs of the corresponding equipments; because both of them exist for obtaining the exergy product. The "c_F" and "c_P" represent unit cost of exergy fuel and exergy product respectively, by which the cost allocation for multiple products can be realized flexibility.

$c_F = \frac{C_F}{Ex_F}$	(7)
$c_P = \frac{C_P}{Ex_P} = \frac{C_F + Z}{Ex_p}$	(8)

2. MFM (Multilevel Flow Model)

MFM is a kind of functional modeling method 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, where special graphs are drawn for MFM model of the target object by using a set of standard symbols as shown in Fig.2 and Table1[6]. Traditionally, MFM has been mainly used in the process control areas for reducing various human-machine system technologies ranging from signal validation, fault monitoring and fault diagnosis to procedure generation and human modeling [7, 8, 9]. While in this study, the application of MFM is extended to represent the semantic structure of the EXCEM model.

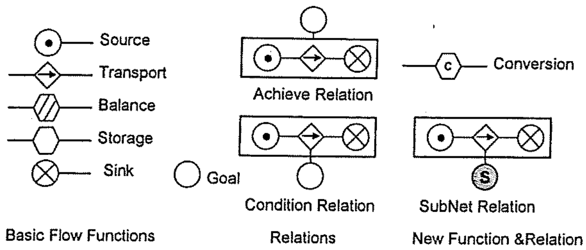

Fig. 2 MFM functions and relations

Table 1 Basic MFM connection and computation rules.

Type	Connection (Input/Output)	Computation rules
Source	Transport(0/1)	Fin=0,Fs=0
Sink	Transport(1/0)	Fout=0,Fs=0
Transport	Source, Balance, Storage and Sink(1/1)	Fin=Fout, Fs=0
Storage	Transport(1/1)	ΔFs=Fin-Fout
Balance	Transport (Multi/Multi)	ΣFin=ΣFout, Fs=0
Conversion	Transport (Multi/Multi)	ΣFin=ΣFout, Fs=0

3 EXCEM-MFM Method

A new analysis method 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 described above as illustrated in Fig.3, together with the flowchart of conducting this method as depicted in Fig.4. Firstly, MFM of exergy, cost, energy and mass are constructed for the target thermal system, if the constructed MFM can pass the checking according to the connecting rules as shown in Table 1, calculation processes among the four kinds of flows will start, otherwise the constructed MFM need to be revised until it can satisfy the rules. In calculation processes, firstly, various physical parameters and mass flow values are calculated by using basic conservation laws of energy and mass based on initial known parameters, and then energy flow values can be obtained. Next step is to calculate exergy flow values by using physical parameters and mass flow values after the reference environment conditions are defined. At last, cost flow values are calculated by using exergy based allocation method based on the calculated exergy flow and cost information concerning with equipments. When all flow values of EXCEM-MFM become known, various performance parameters such as energy efficiency and exergy efficiency, or cost per unit product even CO_2 emission per unit product can be obtained by grouping flow values in MFM.

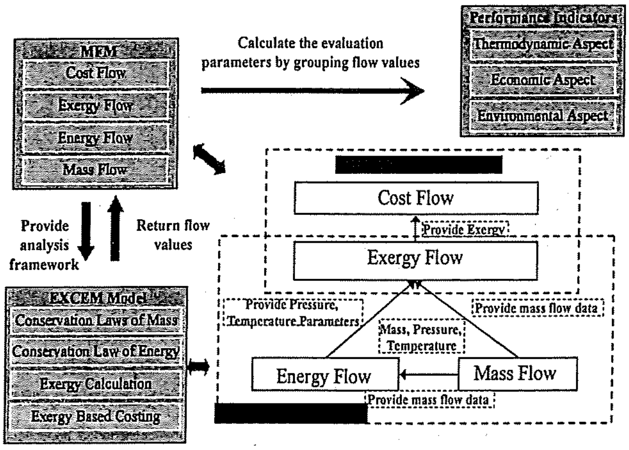

Fig.3 Proposed EXCEM-MFM method.

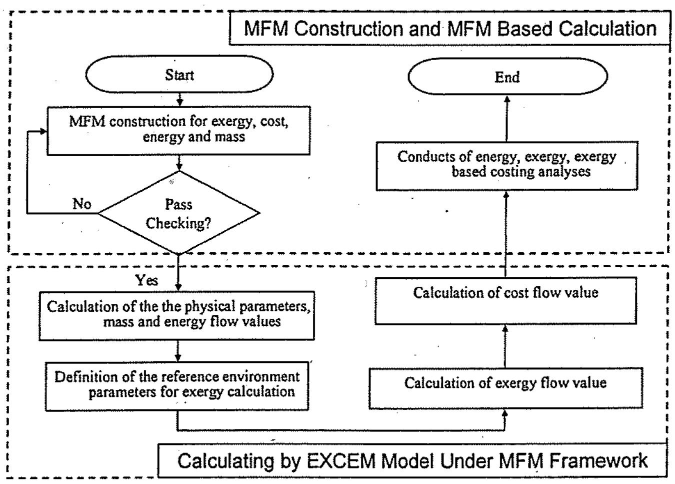

Fig.4 Flowchart of conducting analyses using EXCEM-MFM method.

The representations and physical meanings of mass flow and energy flow had been defined and explained very well in the corresponding past studies. While since MFM applications for exergy and cost appear first time, the basic definitions are necessary. Because 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, similar but not same with energy flow, exergy flow also can be depicted by using MFM, the most important difference between energy MFM and exergy MFM is that the exergy MFM has Sink processes due to exergy destructions in heat exchanges, mechanical frictions, chemical reactions and so on, which do not exist in energy MFM. Furthermore, based on exergy, relevant costs are allocated to form a cost flow. In cost MFM, sources are the costs concerning with equipments always including capital cost and MO costs, sinks mean desired products of the system, and between them are exergy-based cost allocation processes. As mentioned above, different with the flows of exergy, energy and mass constructed based on scientific laws, costs are allocated subjectively depending on type and purpose of a system and other economic considerations. In other word, desired products and exergy based costing processes in cost MFM maybe different for the same thermal system.

Analyses of a HTGR Cogeneration System using EXCEM-MFM Method

A typical HTGR cogeneration system producing hydrogen and electricity simultaneously as shown in Fig.3 will be analyzed based on the proposed EXCEM-MFM model in order to demonstrate its feasibility. Both Gas Turbine High Temperature Reactor 300 (GTHTR300) and Gas Turbine High Temperature Reactor 300Cogeneration (GTHTR300C) of the High Temperature Test Rector (HTTR) project studied by Japan Atomic Energy Agency (JAEA) are very advanced HTGR opinions which are still in the design stage. And, they have been studied from the viewpoints of whole system design concept and safety [9,10]. The economic investigation of GTHTR300 with only one product, electricity also has been conducted by estimating all the relevant cost information associated with the equipments, nuclear fuel, management and operation [11].

However, as for HTGR cogeneration systems such as the GTHTR300C generating hydrogen and electricity simultaneously, although several possible development scenarios with different operating conditions satisfying different demands have been proposed by JAEA and the Japan Atomic Industrial Forum (JAIF) [12], the systems can not attract enough business investments until the feasibility and profitability of them have been demonstrated numerically. Especially, the specific costs per unit hydrogen and electricity have never been calculated for the GTHTR300C due to lack of a broadly acceptable feasible method for allocating system costs to multiple products. Therefore, the performance of the HTGR cogeneration system as shown in Fig.3 will be investigated from thermodynamic and economic aspects based on the proposed EXCEM-MFM model for attracting business investments and fulfilling final deployments.

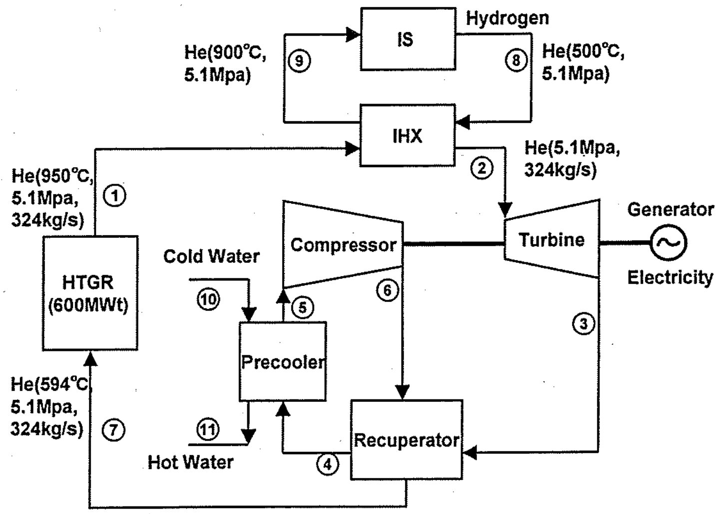

Fig.3 Target HTGR cogeneration system.

Firstly, the basic energy analysis is conducted based on the thermodynamic first law and mass conservation law based on the MFM as shown in Fig.4. The obtained physical parameters will be use to conduct exergy analysis in next step.

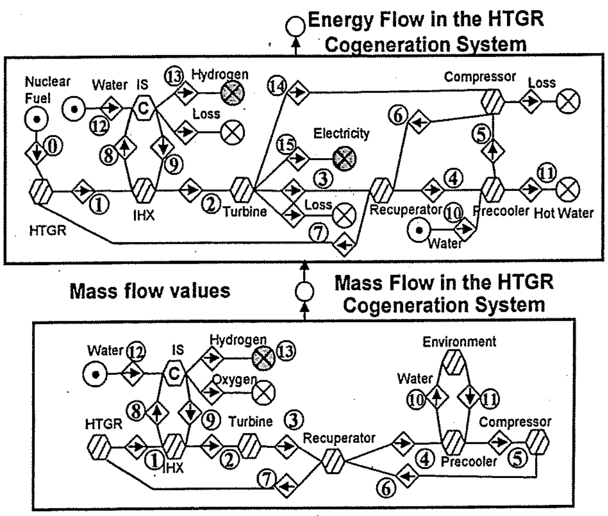

Fig.4 MFM for the basic energy analysis

The exergy MFM of the HTGR cogeneration system is shown in Fig.5, and exergy analysis of equipments and the whole system based on MFM are shown in Table 2.

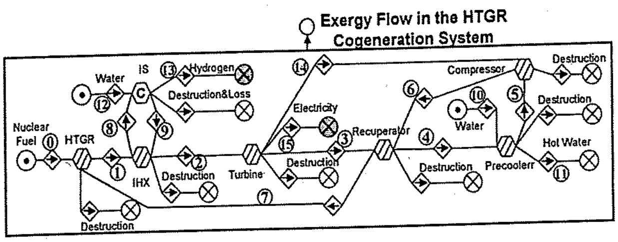

Fig.5 MFM for the exergy analysis

Table 2 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

In this study, the exergy based costing analysis is conducted as shown in Fig.5. The reasoning behind this approach is that the equipments, IHX and IS are considered as existing for producing hydrogen, while the equipments, compressor, turbine, precooler and recuperator are considered as existing for producing electricity, costs associated with the reactor are divided according to exergy consumptions for producing hydrogen and producing electricity. The calculation methods are shown in Eqs.(9) and (10), in which the $Ex_{Reactor,\,P}$ is the exergy product provided by the reactor, and the $Ex_{IHX,\,F}$ is the exergy fuel for the IHX, Z is the cost associated with every equipment.

$Cost_{Hydrogen} = \dfrac{(Z_{IHX} + Z_{IS} + \dfrac{Z_{Reactor}(Ex_{IHX,F})}{Ex_{Reacor,P}})}{Production_{Hydorgen}}$	(9)
$Cost_{Electricity} = \dfrac{(Z_{Recuparator} + Z_{Precooler} + Z_{Compressor} + Z_{Turbine} + Z_{Reactor}(1 - \dfrac{Ex_{IHX,F}}{Ex_{Reacor,P}}))}{Production_{Electricity}}$	(10)

ANALYSIS RESULTS

Based on analysis models described above based on the EXCEM-MFM method and the relevant thermodynamic and cost data, exergy analysis result at the initial operating condition provided by JAEA[10, 12] is shown in Table 3. 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 comparing with other hydrogen and electricity generation systems as shown in Fig.6. Thus the feasibility of the proposed EXCEM-MFM method has been demonstrated practically.

Table 3 Exergy analysis result of the equipments 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

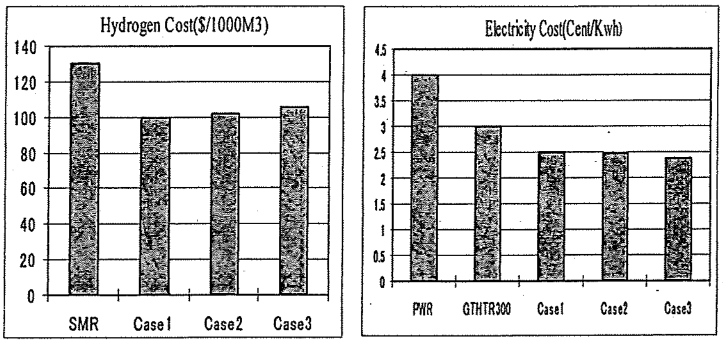

Fig.6 Comparison of the economic performance of the proposed three deployment scenarios of HTGR and other hydrogen and electricity generation systems

CONCLUSIONS

In this study, an integrated and visual method has been proposed based on EXCEM model and MFM to analyze and evaluate performances of thermal systems from thermodynamic and economic aspects comprehensively. Through the application for a typical HTGR cogeneration system, the feasibility and promising application of the proposed EXCEM-MFM method has been demonstrated practically by the obtained findings.

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