OPTIMAL DESIGN OF COGENERATION SYSTEMS BY USING HAMILTONIAN ALGORITHM

Masahide Yanagi,Tsuneo Uekusa,Jun-ichi Yamada* and Kazumasa Shinjo**
NTT Power and Building Facilities INC
3-9-11,midori-cho,musashino-shi,Tokyo 180-0012 Japan
*present affiliation :NTT Advanced Technology Corporation
2-1-13 Bakuro-cho,Chuo-ku,Osaka-shi,Osaka 541-0059 Japan
**ATR Adaptive Communications Research Laboratories
2-2 Hikaridai,Seika-cho,Souraku-gun,Kyoto 619-0288 Japan

ABSTRACT

The optimization of the cogeneration systems (CGS) with the gas engine generator is studied by using the Hamiltonian algorithm (HA). The HA, invented from the study on dynamical systems, is efficient to optimize to design and control the complex systems. The results show that the HA enable us to design the optimal CGS under the objective function about the investment of the plants and the equipment. The HA is also found to be effective to control the optimal CGS operations.

INTRODUCTION

Cogeneration systems (CGS) normally make effective use of both electric power and heat energy from a generator, by a method that obtains two available forms of energy from a single fuel source. Consequently, in addition to being a promising countermeasure to environmental problems by virtue of its available use of energy, CGS is also effective in dealing with the problem of peak power loads as it can be used as a distributed source of electric power.

The key issue in the CGS design is the determination of the system and the machine capacity having the excellent economic and environmental characteristics on the electric power and the heat demand. In general, the ratio of electric power demand to heat demand in general buildings (e.g. office, hotel, and hospital) varies over the course of the year. A CGS, however, features a engaged relationship between the amount of electric-power and heat, and this means that there is a high possibility that excessive or insufficient amounts of electric power or heat will be supplied when applying CGS to these types of buildings. It is therefore necessary to determine the configuration and the capacities depending on the operation plan for each machines. This, however, is generally very complex and a very difficult problem [1]. Against this background, the conventional approach to this problem has been to set rules beforehand for system operation based on follow-up of electric-power, heat demand and so forth, and to carry out evaluations and system operation.

On the other hand, with the goal of evaluating systems having many control variables and performing complex motion, studies have been made on computer simulations for optimizing such a system with respect to a desired objective function. It has been reported that the Hamiltonian algorithm is effective in these optimizing calculations [2-4]. The Hamiltonian algorithm obtains the desired solution by adding conjugate variables to control variables and increasing the degrees of freedom of system motion (creating a high-dimension system) with the aim of promoting autonomous movement between variables. This method is therefore useful in system design and in achieving robust system control in a noisy environment [5].

In the present article, the Hamiltonian algorithm is used to investigate an optimal design of the CGS from the viewpoint of the economy. The article also demonstrates that the Hamiltonian algorithm is an effective tool of an optimal design and an adaptive operation of the CGS.

CGS MODEL

1.Model conditions

The CGS model targeted for study and a comparison model are shown in Figs. 1 and 2. In the CGS model, both electric power and town gas are purchased and electric power is generated by a gas engine (GE), and in addition, exhaust heat is used to deal with cooling and heating loads (heating load included hot water supply demand) in the building. To evaluate the economics and other characteristics of CGS, we employ a comparison model in which only electric power is purchased and a heat pump (HP) is employed for cooling and heating. A CGS requires a GE for generating electric power and an absorption refrigerator (AR) for using exhaust heat, but since the AR deals with cooling and heating loads, a small-capacity HP becomes possible.

The expenditure associated with a CGS consists of initial cost and running cost. Initial cost is the expense of purchasing and installing the required machines, while running cost is the expense of purchasing electric power and town gas for running the system and the expense of maintaining the system. Here, increasing GE capacity to reduce running cost consequently increases initial cost. Conversely, if GE capacity is decreased, initial cost will drop, but the effect of reduced running cost becomes smaller.

There is therefore a tradeoff relationship between initial cost and running cost. This, and the fact that the demand for electric power and demand for heat used in cooling and heating varies with the seasons and the time of day, makes system design a complex task. Nevertheless, the requirement here is to design an economical system that can operate efficiently in the face of these conditions. Here, the objective function we adopt is the number of years (payback period), it takes to recover the initial cost of introducing CGS by reducing running cost, where this initial cost is viewed as additional cost with respect to the above comparison model that does not employ CGS. On the basis of this objective function, we calculate a system for minimizing the payback period and its operating conditions.

The following assumptions are made in regard to the CGS model investigated here.

(1) GE exhaust heat is allowed to be wasted and excess electric power may be generated (excess electric power is not stored by charging).
(2) AR and HP are used to drive cooling and heating in monthly units.
(3) AR and HP are each divided into a maximum of two units.
(4) AR and HP may each be divided unevenly.
(5) GE, AR, and HP machines may have any capacities.
(6) Partial load characteristics of each machine are not considered.

2. Equations for model calculations

<u>Electric power, cooling, and heating load data</u>

The monthly standard for electric-power load (kW), cooling load (kW), and heating load in terms of m month and h hours are given as $d_e(m,h)$, $d_c(m,h)$, and $d_w(m,h)$, respectively.

<u>Machine performance and evaluation data</u>

Given a GE with a maximum input capacity of x_{gm}(kW), let η_{ge} denote its generating efficiency, η_{gt} its exhaust-heat recovery ratio, and $G_g(\eta_{ge}\ x_{gm})$ its initial cost (price of machine including construction expense) in units of JPY1,000. Next, given an AR with a maximum input capacity of x_{am}(kW), let η_{ac} denotes its cooling efficiency, η_{aw} its heating efficiency, and $G_a(\eta_{ac}\ x_{am})$ its initial cost in units of JPY1,000. Finally, given an HP with a maximum input capacity of x_{hm}(kW), let η_{hc} denote its cooling efficiency, η_{hw} its heating efficiency, and $G_h(\eta_{hc}\ x_{am})$ its initial cost in units of JPY1,000. Here, machine cost is approximated by the following equations based on material prices. The terms a_{ij} are approximation coefficients.

$$G_g(\eta_{ge}x_{gm}) = a_{11}\eta_{ge}x_{gm} - a_{12}(\eta_{ge}x_{gm})^{a_{13}} \quad (1)$$

$$G_a(\eta_{ac}x_{am}) = a_{21} + a_{22}\eta_{ac}x_{am} \quad (2)$$

$$G_h(\eta_{hc}x_{hm}) = a_{31}\eta_{hc}x_{hm} - a_{32}(\eta_{hc}x_{hm})^{a_{33}} \quad (3)$$

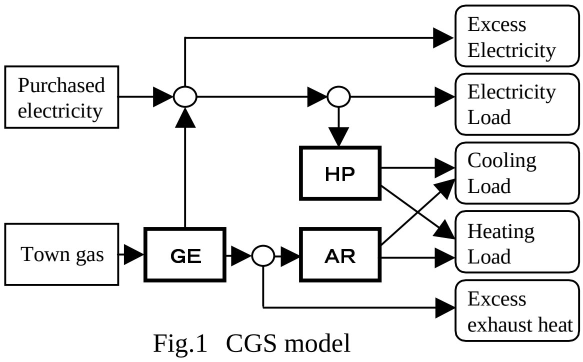

Fig.1 CGS model

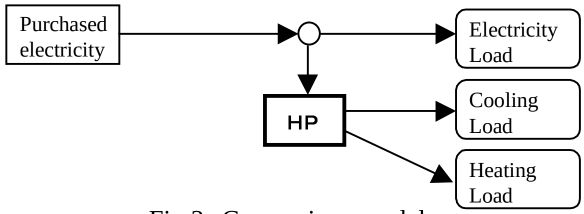

Fig.2 Comparison model

<u>Purchased Electric power, town gas, and CGS maintenance costs</u>

Let x_{em}(kW) denote the peak value per hour of purchased electric power be, x_{es}(kW) its annual cumulative value, and c_{ep}(JPY1,000/kW) and c_{es} (JPY1,000/kWh) the annual base charge (monthly base charge (JPY1,000/kW) * 12 months) and metering charge for electric energy. Next, let x_{gm}(kW) denote the peak value per hour of purchased gas, x_{gs}(kW) its annual cumulative value, c_{gb}(JPY1,000) its flat base charge, and c_{gp}(JPY1,000/kW) and c_{gs}(JPY1,000/kWh) its annual basic metering charge (monthly basic metering charge (JPY1,000/kW) * 12 months) and metering charge for gas energy. Finally, let c_{cm}(JPY1,000/kWh) denote CGS maintenance cost for generated energy. Running cost x_{rce} (JPY1,000) of electric power, running cost x_{rcg} (JPY1,000) of gas including CGS maintenance, and overall running cost x_{rc}(JPY1,000) for one year are therefore given by the following equations.

$$x_{rce} = c_{ep}x_{em} + c_{es}x_{es} \quad (4\text{-}1)$$

$$x_{rcg} = c_{gb} + c_{gp}x_{gm} + (c_{gs} + c_{cm}\eta_{gd})x_{gs} \quad (4\text{-}2)$$

$$x_{rc} = x_{rce} + x_{rcg} \quad (4\text{-}3)$$

<u>CGS model variables</u>

In the calculations, let $x_e(m,h)$ denote purchased electric power, $x_g(m,h)$ purchased gas, $x_{ac}(m,h)$ and $x_{aw}(m,h)$ AR input heat energy for cooling load and heating load, $x_{hc}(m,h)$ and $x_{hw}(m,h)$ HP input electric power for cooling load and heating load, $z_e(m,h)$ excess electric power, and $z_t(m,h)$ excess exhaust heat that is wasted. Each of these variables is non-negative. The following relations can be established between electric power energy, GE exhaust-heat output, cooling load, and heating load.

$$x_e(m,h) + \eta_{ge}x_g(m,h) = d_e(m,h) + x_{hc}(m,h) + x_{hw}(m,h) + z_e(m,h) \quad (5)$$

$$\eta_{gt} x_g(m,h) = x_{ac}(m,h) + x_{aw}(m,h) + z_t(m,h) \quad (6)$$
$$\eta_{ac} x_{ac}(m,h) + \eta_{hc} x_{hc}(m,h) = d_c(m,h) \quad (7)$$
$$\eta_{aw} x_{aw}(m,h) + \eta_{hw} x_{hw}(m,h) = d_w(m,h) \quad (8)$$

Calculating initial cost of dividing machine

HP and AR are each divided into a maximum of two units to deal efficiently with fluctuation in cooling and heating loads. For HP, maximum input capacity x_{hm1}, x_{hm2} in the case of uneven capacity division is given by the following equation for months having no heating load assigned to HP.

$$x_{hm1}(m) + x_{hm2}(m) = \underset{h}{Max}[x_{hc}(m,h)] \quad (9-1)$$

In a similar manner, this capacity is given by the following equation for months having no cooling load assigned to HP.

$$x_{hm1}(m) + x_{hm2}(m) = \underset{h}{Max}[x_{hw}(m,h)] \quad (9-2)$$

We have the following equations for months having cooling and heating loads assigned to HP.

$$x_{hm1}(m) = Max[\underset{h}{Max}[x_{hc}(m,h)], \underset{h}{Max}[x_{hw}(m,h)]\ ] \quad (9-3)$$
$$x_{hm2}(m) = Min[\underset{h}{Max}[x_{hc}(m,h)], \underset{h}{Max}[x_{hw}(m,h)]\ ] \quad (9-4)$$

Maximum input capacities x_{hm1} and x_{hm2} over one year can therefore be expressed as follows.

$$x_{hm1} = \underset{m}{Max}[x_{hm1}(m)] \quad (10-1)$$
$$x_{hm2} = \underset{m}{Max}[x_{hm2}(m)] \quad (10-2)$$

Maximum input capacity x_{am1}, x_{am2} when unevenly dividing AR into two units is given by the following equation for months having no heating load assigned to AR.

$$x_{am1}(m) + x_{am2}(m) = \underset{h}{Max}[x_{ac}(m,h)] \quad (11\text{-}1)$$

Likewise, we have the following equation for months having no cooling load assigned to AR.

$$x_{am1}(m) + x_{am2}(m) = \underset{h}{Max}[x_{aw}(m,h)] \quad (11\text{-}2)$$

We have the following equations for months having both cooling and heating loads assigned to AR.

$$x_{am1}(m) = Max[\underset{h}{Max}[x_{ac}(m,h)], \underset{h}{Max}[x_{aw}(m,h)]\ ] \quad (11\text{-}3)$$
$$x_{am2}(m) = Min[\underset{h}{Max}[x_{ac}(m,h)], \underset{h}{Max}[x_{aw}(m,h)]\ ] \quad (11\text{-}4)$$

Maximum input capacities x_{am1} and x_{hm2} over one year are therefore given by the following equations.

$$x_{am1} = \underset{m}{Max}[x_{am1}(m)] \quad (12\text{-}1)$$
$$x_{am2} = \underset{m}{Max}[x_{am2}(m)] \quad (12\text{-}2)$$

At this time, CGS initial cost x_{ic} is given by the following equation.

$$x_{ic} = G_g(\eta_{ge} x_{gm}) + G_h(\eta_{hc} x_{hm1} + \eta_{hc} x_{hm2}) + G_a(\eta_{ac} x_{am1} + \eta_{ac} x_{am2}) \quad (13)$$

Objective function

In this study, we adopt the payback period commonly used in economic evaluations as the objective function in our optimizing calculations. Letting U denote the payback period, we express it by the following equation in which y_{ic} and y_{rc} are the initial cost and running cost of the comparison model (See Fig. 2) that uses electric power and no town gas.

$$U = (x_{ic} - y_{ic})/(y_{rc} - x_{rc}) \quad (14)$$

HAMILTONIAN ALGORITHM

1.Hamiltonian algorithm [7].

To achieve an optimal design for the CGS model described above, we apply a method called the “Hamiltonian algorithm.” This method has various advantages. For example, it (1) is particularly efficient for problems with many variables; (2) is unlikely to become trapped at local minima; (3) does not require problem transformation to enable it to be applied; (4) is suitable for vector-parallel processing; and (5) does not require careful control of parameters. In addition, convergence to an optimal value becomes easier with this method as the number of variables increases. For these reasons, we apply the Hamiltonian algorithm to our CGS model, which has many variables and for which computation time would normally be expected to increase.

The basic principle and procedure of the Hamiltonian algorithm are described here. The Hamiltonian algorithm is based on a newly proposed information-processing concept called higher dimensioning. The idea here is that solving an optimization problem in the problem space defined for that problem is not as efficient as solving it in a higher dimension space. This principle is illustrated in Fig.3. Here, the meaningful solution that we want to find lies in problem space. However, on examining a solution in a space based on the variables specified by the problem, it will generally exist in a very limited region. This makes it difficult to find the solution. To alleviate this problem, we consider adding extra dimensions to form high-dimension space as a work space. Working in higher dimensions in this way makes problem solving more efficient. Specifically, higher efficiency is achieved by artificially enlarging the cube corresponding to the solution within the

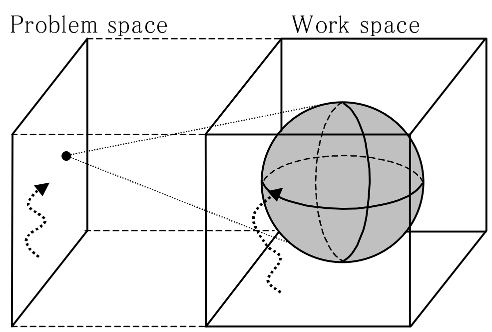

Fig.3 Image of the optimization mechanism

higher dimensional space. In short, we make use of the fact that working in higher dimensional space makes it easier to find the solution than searching for it in relatively small space (problem space).

The method for actually performing higher dimensioning is the Hamiltonian algorithm. It is called this because it utilizes the properties of motion in a dynamic system consisting of many particles. Given the objective function for an optimum-value search problem, the Hamiltonian algorithm expresses the change in the value of that function in terms of the motion experienced by a dynamic system having *N* degrees of freedom corresponding to *N* variables. Then, by using the properties of this motion, the algorithm speeds up the search for an optimum value by generating autonomous motion in the dynamic system in search of the maximum (minimum) value of the objective function. To clarify this process, we explain the optimizing mechanism here. Consider a system of multiple variables that move while interacting with each other. Each variable possesses position and velocity, and the total number of variables is taken to be *N*. If the motion of such variables in this system is observed for a long time, then the frequency τ_x at which position coordinate x_i (i=1,2,….,N) visits the small area bounded by x_i and $x_i + x_i\, dt$ can be given by the following equation[8].

$$\tau_x \propto \left(E - U\left[x_i\right]\right)^{N/2\,\gamma\,-1} \qquad (15)$$

Here, E is a constant that satisfies E-V >0, r is a positive constant, and both E and r are control parameters that speed up optimization. Examining the equation, it can be seen that τ_x is large if N is large or if r is sufficiently small so that N/ 2r-1 > 1. In other words, system motion naturally searches for a position (=solution) that makes the objective function small. This motion, referred to as "autonomous motion," is used in solving the optimization problem. Expressing this autonomous motion, in terms of momentum p_i (i=1,2,….,N), we get the following equations.

$$dx_i / dt = \partial H / \partial p_i \qquad (16\text{-}1)$$
$$dp_i / dt = -\partial H / \partial x_i \qquad (16\text{-}2)$$

Here, rules based on temporal change can also be prepared for momentum p_i, which are new conjugate variables, in addition to position coordinates x_i, the problem variables. Conjugate variables possessing these independent motion rules correspond to "new dimensions" in the higher dimensioning method described above. In high-dimension space (work space) of Fig.3, p_i takes on various values with respect to one x_i , and as a result, the area corresponding to the solution expands in the manner of a sphere. Here, the Hamilton characteristic function H at a mass point (mass=1) receiving potential energy (position energy U) can be given by the following equation [9-10].

$$H = \frac{1}{2}\sum_i p_i^2 + U\left(x_1, x_2, \cdots x_n\right) \qquad (17)$$

If we now eliminate the characteristic function and momentuma, we get the following equation.

$$d^2 x_i / dt^2 = -\partial U / \partial x_i \qquad (18)$$

This equation equates the force received from potential to accelerated motion. Based, therefore on the force that each variable receives from the objective function, motion is calculated by the Verlet method [11] so as to converge to the minimum value of the objective function.

2.Application to CGS optimal design

Application of the Hamiltonian algorithm to the problem of CGS optimal design is described as follows. Here, in order to apply Eq. (18) to this problem, we establish a correspondence between the position of moving particles and the variables that express CGS-model energy, and set payback period, the objective function, to potential energy (U) received by particles. Then, by solving Eq. (18), particle visiting time becomes maximum at the minimum value of the objective function, that is, payback period. Particle position can then be calculated for minimum objective function, and the corresponding CGS-model energy variables that minimize payback period can then be calculated. In actual calculations, the CGS-model energy variables of eliminating $x_e(m,h)$, $x_g(m,h)$, $x_{ac}(m,h)$, $x_{aw}(m,h)$, and $z_e(m,h)$ are reduced by the relationship between Eqs. (5) to (8) and variables $x_e(m,h)$ and $z_e(m,h)$, thereby selecting $x_{hc}(m,h)$, $x_{hw}(m,h)$, and $z_t(m,h)$ corresponding to the moving particles. In this way, we assume the movement of mass points in 1728 [=3 (number of selected variables) * 12 (months) * 24 (hours) * 2 (position and velocity)] dimensional phase space, track change in movement at very small intervals with the force received from the objective function treated as acceleration, and perform optimization. The range in which each variable can change and the acceleration calculated from the objective function is explained in more detail in the appendix.

TYPES OF DATA AND METHOD OF EVALUATING CALCULATION RESULTS

1.Types of data

The types of data used in the optimizing calculations of this CGS model are described below. The number of convergence calculations is 300,000.

Load data

We assume a building with a total floor space of 20,000 m^2 as load data, composed of office and hotel with a each floor space of 10,000 m^2. Here, cooling and heating demand exists at the same time. In addition, heating load includes heat for supplying hot water in addition to heat for heaters. The monthly fluctuations in load for electric power, cooling, and heating with respect to time of day are shown in Figs.4, 5, and 6.

Machine price

Approximating equations were derived from the market price of machines of various manufacturers including installation (Eqs. 1 to 3). Coefficients when output capacity and price are given in units of kW and JPY1,000 are listed in Table 1. In this report, machine price is determined on the basis of total capacity even for dividing machine; cost disadvantage due to the use of dividing machine is not considered here.

Charge data

Coefficients used in calculating electric power and town gas charges and the cost of CGS maintenance are listed in Table 1 when consumption and charges are given in units of kW and JPY1,000. Here, annual running cost is calculated on the basis of 30-day months.

Comparison model

Initial cost and running cost of the comparison model when using the above data are y_{ic}=108,882 and y_{rc}=146,433 (in units of JPY1,000).

2.Calculations by a simple technique

To evaluate the calculation results obtained by the optimizing technique described above, we calculate the economic characteristic of a CGS using a simple calculation technique using the data described in section 1.

This simple calculation technique is as follows.

(1) GE capacity is determined beforehand.
(2) The GE is driven by electricity oriented operation. (Generation is performed up to rated output as long as there is demand for electric power.)
(3) Exhaust heat is used in the order of heating load ⇒ cooling load.
(4) AR capacity is determined by the maximum objective of exhaust heat to be used for cooling and heating loads.
(5) HP capacity is determined on the basis of the maximum amount of cooling and heating loads that cannot be covered by exhaust heat.
(6) GE exhaust heat is allowed to be wasted. Excess electric power is not used for charging.
(7) AR and HP are operated for either cooling or heating in monthly units.
(8) AR and HP are each divided into two units evenly. Capacity per unit is arbitrary.
(9) Partial load characteristics of each machine are not considered.

Using the above simple calculation technique, we

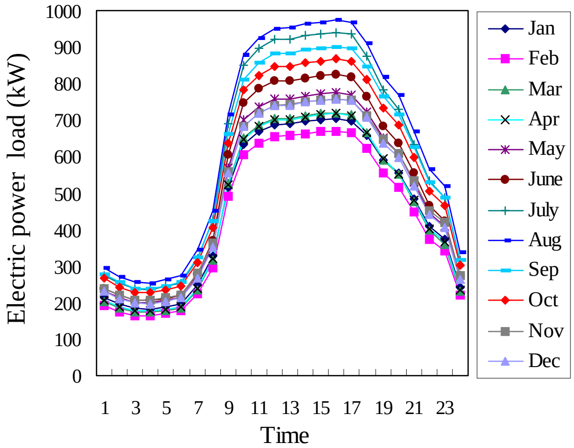

Fig.4 Building Electric power load

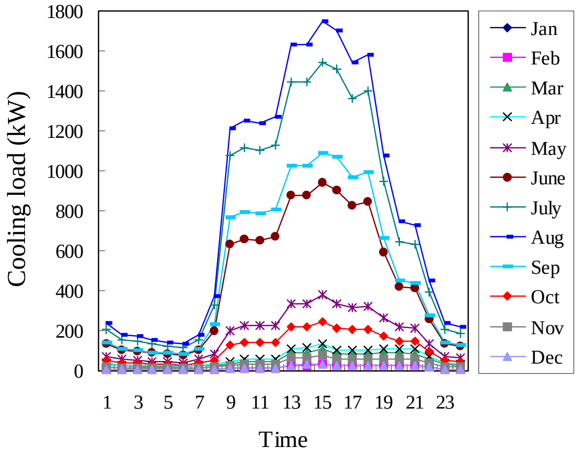

Fig.5 Building cooling load

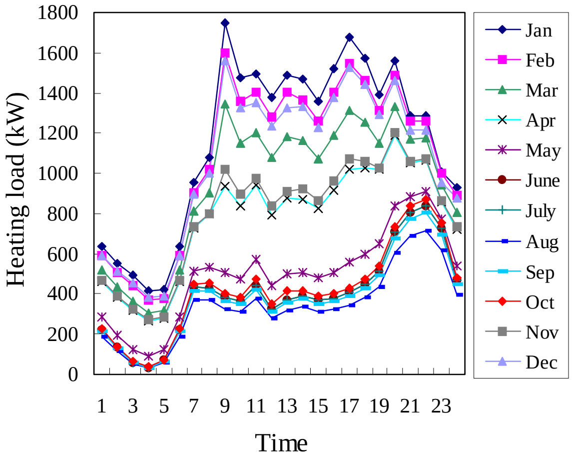

Fig.6 Building heating load

Table 1 List of coefficient

item	coefficient	item	coefficient
a_{11}	380	c_{gb}	540
a_{12}	3.1	c_{gp}	1.184
a_{13}	1.5	c_{gs}	0.06678
a_{21}	10000	c_{cm}	0.105
a_{22}	55	η_{ge}	0.3
a_{31}	95	η_{gt}	0.5
a_{32}	11	η_{ac}	0.7
a_{33}	1.2	η_{aw}	0.9
c_{ep}	18.72	η_{hc}	3.0
c_{es}	0.48	η_{hw}	3.0

consider three cases as follows.

Case 1: Calculations assume that GE capacity is the minimum value (200 kW) of the annual electric power load that can be handled by GE annual rated output.

Case 2: Using the GE capacity (339 kw) obtained from the optimizing calculations that minimized the payback period by the Hamiltonian algorithm, calculations are repeated using the above calculation technique.

Case 3: Optimal designing calculations are performed considering operation by the Hamiltonian algorithm.

3.Evaluation indexes

As described above, the payback period determined from the differences between the initial costs and running costs of the CGS model and comparison model is used as an objective function for optimizing calculations. In addition, the following indexes are established to evaluate the efficiency and energy-saving characteristics of the calculated system.

Overall efficiency (%) = (generated-electric-power + heat-exhaust - wasted-heat-exhaust - wasted-electric-power) / consumed gas

Energy-saving efficiency (%) =(comparison-model-input-energy - CGS-model-input-energy) / comparison-model-input-energy

CALCULATION RESULTS

1.Comparison with the simple calculation technique

The calculation results for the CGS model using the Hamiltonian algorithm (Case 3) are compared with Case 1 and Case 2 in Figs. 7 to 12.

The payback period is smallest in Case 3, being smaller by one year compared to Case 1 and by 0.4 year compared to Case 2. Running cost is smallest in Case 3, and initial cost in this case is also smaller than that of Case 2. The reason for reduced initial cost here is that AR capacity is made small. However, regardless of reduced AR capacity, there is hardly any wasted exhaust heat in Case 3, and this makes for available use of exhaust heat. As a result, therefore, of optimal design taking into account operation of equipment and uneven division, initial cost can be decreased, and at the same time, running cost and payback period can be reduced, compared to Case 2.

As for overall efficiency, Case 2, in which GE capacity is large without consideration of operation, wasted heat increases and efficiency drops compared to Case 1 that performs GE rated output all the year round. On the other hand, Case 3 is even more efficient than Case 1, demonstrating that operation-oriented design can produce a highly efficient system. In terms of energy saving, Case 1 and Case 2 give results opposite to those for overall efficiency due to differences in the scale of GE. Case 3, on the other hand, which exhibits high overall efficiency compared to Case 2 for the same scale of GE, achieves higher energy-saving effect.

2.Annual machine usage conditions

Next, focusing on Case 3, Figs. 13 and 14 show annual machine usage conditions for load assigned to each machine at times of peak cooling and heating loads in each month. For AR, the output ratio between cooling and heating is 1:1.29, and for GE,

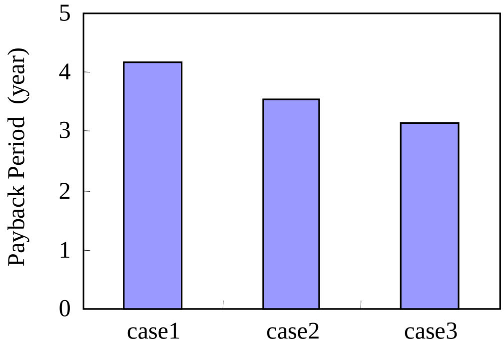

Fig.7 Comparison of Payback period

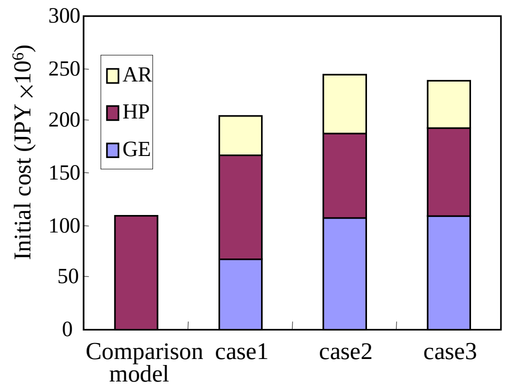

Fig.8 Comparison of initial cost

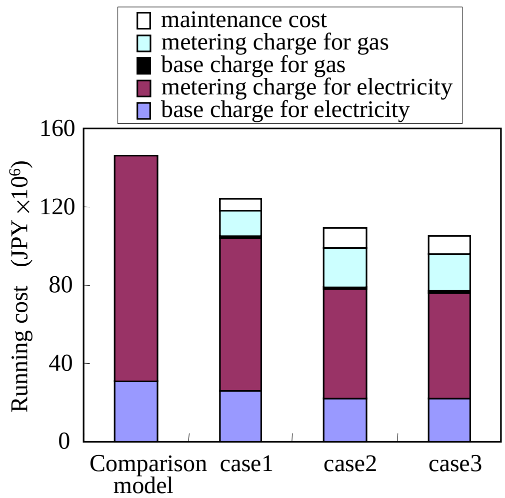

Fig.9 Comparison of running cost

rated output for the most part is achieved at the times of peak loads in each month.

As for the capacity of equipment, that for the large-capacity machine of the two allocated to both HP and AR is determined on the basis of cooling load in August, and that of the small-capacity machine is determined on the basis of heating load in September.

Switching operation between machines to handle cooling and heating loads is performed in the summer. The large capacity HP machine is assigned to cover either cooling or heating load if large in a certain month, while the large-capacity AR machine is assigned to the larger of the cooling- and heating-load portions covered by exhaust heat. The reason for this approach is to make use of exhaust heat as effectively as possible.

Based on the above, the four units of equipment (AR1, AR2 that receive exhaust heat from GE, and HP1, HP2) are each given an appropriate amount of cooling and heating load to handle each month, demonstrating that machine operation is taken into account in CGS optimal design using the Hamiltonian algorithm.

CONCLUSIONS

In this report, we have investigated a method for CGS optimal design from the economical viewpoint. This method uses the Hamiltonian algorithm, an effective tool in optimizing calculations for systems having many variables and exhibiting complex motion. This method enables the CGS to be optimized in terms of the payback period without the system operation rules following up the electric-power and heat demand. The effect of divided unit on the payback period was also clarified here. In short, it was shown that the Hamiltonian algorithm is effective in the design of optimal CGS with factor into operation. This kind of evaluation method is thought to be an effective approach for performing detailed calculations for optimal design of ideally operating system and obtaining associated operating conditions. We are currently at the stage where the effectiveness of basic operations in optimizing calculations has been verified. Improvements must now be made to

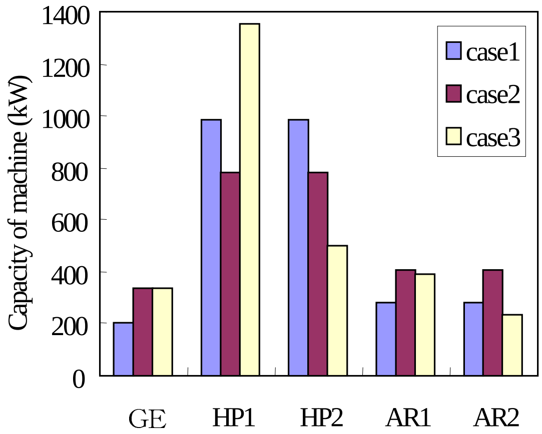

Fig.10 Capacity of machine

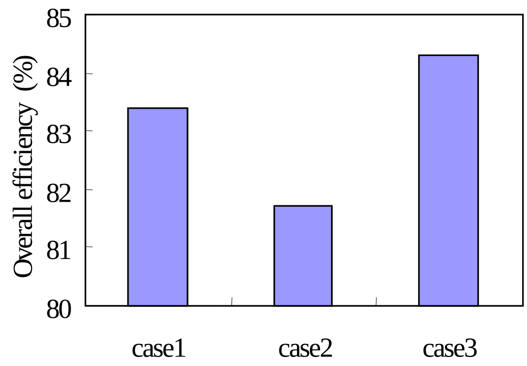

Fig.11 overall efficiency

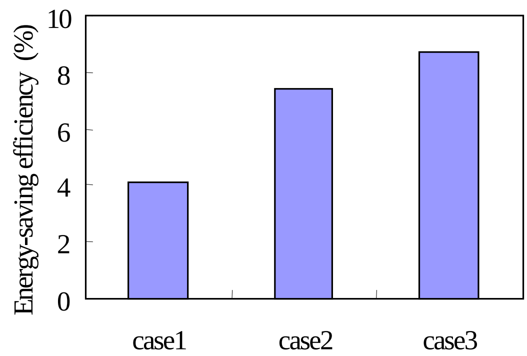

Fig.12 Energy-saving efficiency

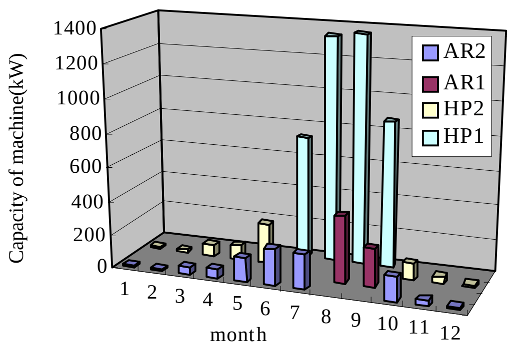

Fig.13 Annual machine usage conditions
(at time of peak **cooling** loads in each month)

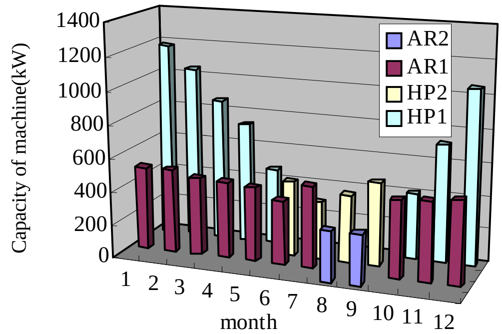

Fig.14 Annual machine usage conditions
(at time of peak **heating** loads in each month)

achieve a calculation method that does not hold up in local minimum point, that is, parameters for reiterative calculations must be optimized, a cost calculation method when adopting divided unit must be enhanced, etc. Overall, expanding the application of this method will be investigated, such as optimizing with another objective function and applying to another type of energy system.

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APPENDIX

The following shows the range of possible movement for the $x_{hc}(m,h)$, $x_{hw}(m,h)$, and $z_t(m,h)$ variables and the expansion equations for calculating acceleration when the initial cost is represented by Eq. 13. True [ ] in the following is a function that becomes 1 when the contents of [ ] is true and 0 when false.

- $x_{hc}(m,h)$

$0 \le x_{hc} \le d_c / \eta_{hc}$

$$\frac{\partial U}{\partial x_{hc}} = \frac{1}{y_{rc}-x_{rc}}\frac{\partial x_{ic}}{\partial x_{hc}} + \frac{x_{ic}-y_{ic}}{(y_{rc}-x_{rc})^2}\frac{\partial x_{rc}}{\partial x_{hc}}$$

$$\frac{\partial x_{ic}}{\partial x_{hc}} = \frac{\partial G_g}{\partial x_g}\frac{\partial x_g}{\partial x_{hc}} + \frac{\partial G_g}{\partial x_{ac}}\frac{\partial x_{ac}}{\partial x_{hc}} + \frac{\partial G_h}{\partial x_{hc}}$$

$$\frac{\partial G_g}{\partial x_g} = \left(a_{11}\eta_{ge} - a_{12}a_{13}\eta_{ge}{}^{a_{13}} x_{gm}{}^{a_{13}-1}\right) True\left[x_g = x_{gm}\right]$$

$$\partial x_g / \partial x_{hc} = -\eta_{hc} / (\eta_{gt}\eta_{ac})$$

$$\partial G_a / \partial x_{ac} = a_{22}\eta_{ac}\big(True\left[x_{ac} = x_{am1}\right] + True\left[x_{ac} = x_{am2}\right]$$

$$\partial x_{ac} / \partial x_{hc} = -\eta_{hc} / \eta_{ac}$$

$$\partial G_h / \partial x_{hc} = \left(a_{31}\eta_{hc} - a_{32}a_{33}\eta_{hc}{}^{a_{33}} x_{hm}\right) \times \left(True\left[x_{hc} = x_{hm1}\right] + True\left[x_{hc} = x_{hm2}\right]\right)$$

$$\frac{\partial x_{rc}}{\partial x_{hc}} = \frac{\partial x_{rce}}{\partial x_e}\frac{\partial x_e}{\partial x_{hc}} + \frac{\partial x_{rcg}}{\partial x_g}\frac{\partial x_g}{\partial x_{hc}}$$

$$\partial x_{rce} / \partial x_e = c_{ep} True\left[x_e = x_{em}\right] + c_{es}$$

$$\partial x_{rcg} / \partial x_g = c_{gp} True\left[x_g = x_{gm}\right] + c_{gs} + c_{cm}\eta_{ge}$$

$$\partial x_e / \partial x_{hc} = 1 - \eta_{ge}\partial x_g / \partial x_{hc}$$

- $x_{hw}(m,h)$

$0 \le x_{hw} \le d_w / \eta_{hw}$

$$\frac{\partial U}{\partial x_{hw}} = \frac{1}{y_{rc}-x_{rc}}\frac{\partial x_{ic}}{\partial x_{hw}} + \frac{x_{ic}-y_{ic}}{(y_{rc}-x_{rc})^2}\frac{\partial x_{rc}}{\partial x_{hw}}$$

$$\frac{\partial x_{ic}}{\partial x_{hw}} = \frac{\partial G_g}{\partial x_g}\frac{\partial x_g}{\partial x_{hw}} + \frac{\partial G_a}{\partial x_{aw}}\frac{\partial x_{aw}}{\partial x_{hw}} + \frac{\partial G_h}{\partial x_{hw}}$$

$$\partial x_g / \partial x_{hw} = -\eta_{hw} / (\eta_{gt}\eta_{aw})$$

$$\partial G_a / \partial x_{aw} = a_{22}\eta_{aw}\left(True\left[x_{aw} = x_{am1}\right] + True\left[x_{aw} = x_{am2}\right]\right)$$

$$\partial x_{aw} / \partial x_{hw} = -\eta_{hw} / \eta_{aw}$$

$$\partial G_h / \partial x_{hw} = \left(a_{31}\eta_{hw} - a_{32}a_{33}\eta_{hw}{}^{a_{33}} x_{hm}\right) \times \left(True\left[x_{hw} = x_{hm1}\right] + True\left[x_{hw} = x_{hm2}\right]\right)$$

$$\frac{\partial x_{rc}}{\partial x_{hw}} = \frac{\partial x_{rce}}{\partial x_e}\frac{\partial x_e}{\partial x_{hw}} + \frac{\partial x_{rcg}}{\partial x_g}\frac{\partial x_g}{\partial x_{hw}}$$

$$\partial x_e / \partial x_{hw} = 1 - \eta_{ge}\,\partial x_g / \partial x_{hw}$$

- $z_t(m,h)$

$z_t \ge 0$

$$\frac{\partial U}{\partial z_t} = \frac{1}{y_{rc}-x_{rc}}\frac{\partial x_{ic}}{\partial z_t} + \frac{x_{ic}-y_{ic}}{(y_{rc}-x_{rc})^2}\frac{\partial x_{rc}}{\partial z_t}$$

$$\frac{\partial x_{ic}}{\partial z_t} = \frac{\partial G_g}{\partial x_g}\frac{\partial x_g}{\partial z_t}$$

$$\partial x_g / \partial z_t = 1/\eta_{gt}$$

$$\frac{\partial x_{rc}}{\partial z_t} = \frac{\partial x_{rce}}{\partial x_e}\frac{\partial x_e}{\partial z_t} + \frac{\partial x_{rcg}}{\partial x_g}\frac{\partial x_g}{\partial z_t}$$

$$\partial x_e / \partial z_t = -\eta_{ge}\,\partial x_g / \partial z_t$$